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FUEL CHANNEL REFILLING - DATA ANALYSIS

by

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ABSTRACT

Analysis of existing data on fuel channel refilling is presented. The analysis focuses on the data obtained using the Stern Laboratories Cold Water Injection Test (CWIT) Facility. The two-fluid model thermal-hydraulics computer code CATHENA is also used to simulate experimental results on fuel channel refilling from both the CWIT and RD-14 facilities. Conclusions related to single and double break tests, including the effect of non-condensible gases, are presented. Moreover, a set of recommendations is given for further analysis and separate effect experiments.

RÉSUMÉ

Le présent rapport analyse les données expérimentales existantes sur le remplissage des canaux de combustible. L'analyse porte sur les données obtenues à partir de l'installation d'épreuves à injection d'eau froide [Cold Water Injection Test (CWIT)] des laboratoires Stern. Le code machine thermohydraulique, CATHENA, qui utilise deux fluides a aussi servi à simuler les résultats expérimentaux du remplissage des canaux de combustible autant dans l'installation d'épreuves à injection d'eau froide que dans les installations RD-14. Les conclusions des épreuves de rupture simple et double, y compris l'effet des gas non condensable, sont présentées. En outre, une série de recommandations est présenté en vue d'analyses supplémentaires et d'expériences distinctes sur certains effets.

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EXECUTIVE SUMMARY

The objectives of this project, performed for the Atomic Energy Control Board (AECB), were to (i) analyse in detail the experimental data on CANDU type feeder/channel refilling obtained using the Cold Water Injection Test (CWIT) facility; (ii) review the overall nature of the refilling experiments carried out using the RD-14 facility, and (iii) evaluate the two-fluid model code CATHENA in predicting the refilling characteristics of representative tests.

Analysis of the CWIT data showed that the overall refilling process is controlled by feeder refilling. Once one of the feeders is refilled, channel refilling is accomplished by hydrostatic pressure difference between the feeders as well as the imposed injection pressure. However, under the condition of near zero header-to-header pressure difference, typical of the double break tests, feeder refilling delay can take place. Feeder refilling delay can be very significant particularly when simultaneous non-condensible gas injection is applied. It is apparent from the present results that the criteria for the onset of counter-current flow limitation (CCFL) and the carry-up limit in typical CANDU feeder geometries are more restrictive than published criteria based on simple geometries. Detailed analysis of the quenching and refilling front propagation throughout the loop was carried out. The overall characteristics were analysed in terms of initial and boundary conditions.

A general overview of the RD-14 experimental program on channel refilling was also carried out. This overview is given in Appendix B of this report.

The CATHENA thermal-hydraulic code was used to simulate two CWIT tests representing typical single and double break tests. It was also used to simulate a small break test carried out in the RD-14 test facility. In general, the code predictions were in good agreement with the experimental results.

Based on the present work, recommendations were made to perform detailed analysis of the RD-14 data and to carry out additional experimental work related to feeder rewetting and refilling characteristics.

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A. INTRODUCTION

In CANDU[*] reactors, fuel channel refilling is an important phase of LOCA[**] analysis since the refilling process determines the effectiveness of the emergency coolant injection system. The complete refilling process involves not only the fuel channel itself but also the refilling of the feeders connecting the inlet and outlet headers to a given fuel channel. In some postulated loss of coolant accidents, near zero header to header pressure difference can exist resulting in flow stagnation in the fuel channel. Cold water injection under such scenarios can result in complex thermal-hydraulic phenomena which need to be examined. Accordingly, a large body of experimental data related to the process of rewetting and refilling of a "hot" fuel channel with "cold " water was generated. It includes data from the cold water injection test (CWIT) facility and the RD-14 test facility.

The objectives of the present work are to:

(i) review and analyze the experimental data on fuel channel refilling and the associated phenomena obtained from the CWIT facility,

(ii) provide an overview of the RD-14 experiments on the same subject, and

(iii) evaluate the two-fluid computer code CATHENA in predicting the characteristics of fuel channel refilling by comparing its predictions with selected tests.

[*] Canadian-Deuterium-Uranium

[**] Loss Of Coolant Accident

B. THE CWIT EXPERIMENTS

An extensive experimental program was conducted by the Canadian Nuclear Industry using the CWIT test facility [1-13]. The objective of this test program was to provide experimental data to be used for modelling thermal-hydraulic phenomena taking place during the different phases of LOCA and for verification of computer codes.

The data obtained from a large number of these experiments are analyzed in this report. The experiments analysed in the present work are:

(i) Feeder and channel refilling tests reported in Refs. [1-4] (reports WNRE-613, CWAPD-480, CWAPD-481 and SL-010).

(ii) Non-condensible gas injection tests reported in Ref. [5] (report CWAPD-460).

(iii) Flow stratification tests reported in Ref. [6] (report CWAPD-433).

(iv) Channel refilling tests reported in Refs. [7-13].

1. Experimental Arrangement

1.1 Test Facility

The CWIT facility represents a full geometrical scale CANDU reactor channel-feeder system. The test facility, shown in Figures 1 and 2, consists of two 6 m horizontal test channels, two headers, inlet and outlet feeders, two break simulation devices, various pressure and control systems and inter-connecting piping. The test channel assembly contains a 6 m electrically heated 37-element fuel string. The fuel string has a design heat flux of 5 Watts/cm^2 and a uniform axial power distribution. A radial power depression ratio of 1.0/0.81/0.72/0.68 is maintained by setting the required voltages to the individual rings during the tests. End fitting flow simulators are installed at both ends of the channel and connected to the inlet and outlet feeders.

The inlet and outlet headers are located 10 meters above the bottom channel. The headers have an overall length of 1.23 m each and are made from 250 mm diameter carbon steel pipe (10 inch schedule 120) with several 50 mm flanged connections. The feeder connections to the headers are at an angle of 45 degrees below the horizontal center line of the header. For both single and double break configurations, the break lines from the headers are connected to the top exit nozzles.

The break simulation devices consist of pneumatic quick acting valves and an orifice flange of 50 mm in diameter which can be fitted with various sizes of break orifices. The break orifices are located downstream of the quick acting valves. The 50 mm break lines are enlarged downstream of the orifices to 200 mm blowdown lines which are piped to the blowdown tank. Other 100 mm break lines are installed in parallel with the 50 mm break lines. Either the 50 mm or 100 mm break lines can be used while the other break lines are blanked off. The effluent vapour is condensed in the blowdown tank by water spray. The water in the blowdown tank is transferred to a storage tank by an extraction pump. Pressure in the blowdown tank can be controlled up to a maximum of 5 MPa by controlling the liquid level and injection of air or nitrogen gas.

The inlet and outlet feeders are made from 50 mm and 75 mm carbon steel pipes (2 and 3 inch schedule 80) and are symmetrical. Some changes in the feeder geometry have been made during the test program. Such changes will be identified during the analysis of the various stages of the test program.

The high pressure injection water system consists of a pump (maximum flow rate of 6 L/s and shut-off head of 580 m), a 3.2 m^3 tank filled with high pressure water and nitrogen gas, a pressure control valve installed on a by-pass line, a 50 mm check valve, 50 mm venturi meters, K orifices, isolation valves (one of the isolation valves is closed in the single ended injection mode), 50 mm piping and a temperature control system. This system is capable of supplying subcooled injection water to either or both of the inlet and outlet headers up to the maximum flow rate of 6 L/s, at pressure and temperature of 3 MPa and 100 °C.

The test loop can be preheated by superheated steam to 300 °C, or by circulation of saturated water to 250 °C, both supplied by a fossil boiler. The effluent preheat steam or saturated water is returned to a condenser via a steam separator and a pressure control valve.

1.2 Instrumentation

The locations and designations of various loop instrumentation devices are shown schematically in Figure 2. The pressure tube surface thermocouples are shown in Figure 3. The fuel string is instrumented with thermocouples at sixteen axial planes and seven cross-sections as shown in Figure 4. A data acquisition system based on a Hewlett-Packard 1000 mini-computer was used.

1.3 Test Conditions

All CWIT tests analyzed in this report (except those listed under items (iii) and (iv) in page 2) were performed with the injection pressure held constant at 1.5 MPa at the pump discharge downstream of the injection tank and the water injection temperature of 30 °C. The blowdown tank pressure was kept at 0.2 MPa. Several arrangements of break orifices were used. These included single and double break tests with break sizes ranging between 1 to 100% . The double break configurations included symmetrical and asymmetrical break tests. The channel power used during testing was either 50 kW or zero.

1.4 Test Procedures

Following is the test procedure used in all tests, except those listed under item (iii) in page 2.

Superheated steam was initially circulated to preheat the test loop to temperatures between 200 and 300 °C with both break valves closed and the effluent valve open. An isolation valve in the inlet header injection line was closed to direct the preheated steam to the inlet header, feeder, the channel, and finally the outlet header where the effluent was returned to a condenser via effluent and pressure control valves. The preset power level to the fuel string was established during the preheating of the test loop.

When uniform temperatures were obtained throughout the test loop, the manual control valves for both preheat steam and the effluent were isolated. Then, the initial loop pressure and desired injection and blowdown tank pressures were established. The preset power to the fuel string was then turned on and the computer data scanning was initiated at the preset scanning rates.

When the heater rod surface temperature reached the prescribed temperature, the quick acting preheat steam (located near the inlet header) and the effluent (located near the outlet header) isolation valves were closed while the quick acting break valves (one in case of single break tests) were opened to initiate the blowdown. When the system pressure decreased below the injection pressure, water was injected into the header to start the refilling process.

The test was terminated when all of the heater rod surface temperatures had either cooled down or the maximum temperature of 780 °C was reached. The power to the fuel string was automatically turned off if the computer registered a heater surface rod temperature above 780 °C in three consecutive scans.

2. Analysis of the CWIT Results

2.1 The Refilling Process

Following is a general qualitative description of the channel-feeder refilling as deduced from the experimental results. In the following sections "surface quenching" is identified by sudden drop of the surface temperature from its initial value to the prevailing saturation temperature while "refilling" is achieved when the surface temperature decreases below saturation.

In both single break and double break tests, the refilling process starts by water injection into the headers which is initiated when the system pressure is reduced below a pre-set value (1.5 MPa in most recent data). For single break tests, the injected water flows down the inlet feeder . The loop undergoes the following sequence of events: inlet feeder quenching, inlet feeder complete refill, channel quenching and refill and finally outlet feeder quenching and refill. The flow is obviously directed through the loop out of the break side.

In the double break case, near zero header-to-header pressure drop exists. The injected water flows down both feeders quenching their walls. However, the quenching process appears to favor one of the feeders in which the quench front advances down faster than the other until this favored feeder is completely refilled. As this prefered feeder is filled, a hydrostatic head is established pushing the steam-water mixture out of the other feeder through its header. The channel is then refilled followed by complete refilling of the second feeder.

The experimental data showed that the most important phenomenon governing the overall loop refilling is that of feeder refill. Significant delays in complete loop refill can occur due to steam-water counter-current flow in the feeders. Steam venting in the double break case has to take place, at least initially, in opposite direction to injected water.

Quantitative analysis of the results is given in the following sections.

2.2 Feeder Refilling

In this section, analysis of data from four refilling test reports, consisting of a total of 110 tests, is presented. These reports are WNRE-613 (Ref. [1]), CWAPD-480 (Ref. [2]), CWAPD-481 (Ref. [3]) and SL-010 (Ref. [4]). The tests presented in these references were all double break tests. The main objective of these tests was to investigate the feeder refill behaviour following a blowdown phase during a range of postulated loss of coolant accidents (LOCA) in the CANDU type nuclear reactor. The parameters investigated were the initial feeder preheat temperature, break size and channel power.

In Ref. [1], 47 tests, consisting of 21 single-channel tests (bottom channel only) and 26 parallel-channel tests, were presented. In these tests, the loop was set up in the symmetric double break and double injection configuration to achieve a condition of near zero header to header pressure drop.

In Ref. [2], 21 tests, consisting of 15 single channel tests (bottom or top channel) and 6 parallel channel tests, were reported. These were double injection tests and included both symmetrical and asymmetrical double break tests.

In Ref. [3], 20 tests, consisting of 12 single channel (top or bottom channel) tests and 8 parallel channel tests were reported. These were symmetric double break and double injection tests.

In Ref. [4], 22 tests, consisting of 11 single channel tests (bottom channel only) and 11 parallel channel tests, were reported. These were symmetric double break and double injection tests.

It should be noted that during the above testing program changes to the feeder geometry were made. The first set of tests, presented in Ref. [1], were conducted with 50 mm diameter feeder connections to the headers and 50 mm header nozzles. The rest of the above refilling tests were conducted after replacing the 50 mm connections to the headers and the 50 mm header nozzles by 75 mm ones. Moreover, for the test series presented in Ref. [4], the 75 mm uppermost horizontal feeder section was inclined upward by approximately one pipe diameter at the first vertical 90° elbow after the 75 mm header nozzle connection. This inclined section contained thermocouples numbers 37 and 38 or 55 and 56 shown in Figure 2.

2.2.1 General Parametric Effect

In this section the overall characteristics of feeder refilling are examined. Detailed examination of the process will be presented in subsequent sections.

In the aforementioned refilling test reports, feeder refill times were plotted against the initial feeder preheat temperature. The feeder refill time, as defined in Ref. [1], was taken as the time between the arrival of cold water at the top-most feeder thermocouple locations (17 and 23 for the top channel in Figure 5, and 25 and 31 for the bottom channel in Figure 6) and the indication of 100% liquid by the densitometers located near the fuel channel elevation (at locations 1 and 2 for the top channel in Figure 5, and 3 and 4 for the bottom channel in Figure 6). For each particular test, the feeder refill time was calculated for the feeder which was refilled first. However, these times were plotted against the initial temperature of the geometrical outlet feeder even when the inlet feeder was refilled first. Since it is believed that the feeder heat capacity is one of the factors controlling the refilling time and since the initial geometrical inlet feeder temperature was always higher than that of the geometrical outlet feeder by up to 60 °C, due to the method of heating (injecting steam from the inlet header to the outlet header via the channel), it is more appropriate to consider the initial temperature of the feeder which was refilled first to be plotted against the refilling time of that feeder. This procedure is followed in the present analysis.

The effect of initial feeder temperature, channel power and break size on feeder refill time are shown in Figure 7. It is clear that the feeder refill time increases with initial tube temperature due to higher vapour generation during feeder quenching and refilling. Figure 7 also shows that decreasing the break size resulted in longer feeder refill time. This could be attributed to the increased resistance to steam venting, caused by the smaller orifice size. Moreover, the smaller the break the higher is the system pressure, as will be discussed later (see Figure 29). It is well well known that the rewetting (or quenching) velocity, and consequently the vapour generation rate, increases with increasing system pressure. The increase in rising vapour velocity can delay the complete refilling of the feeder due to counter-current flow phenomenon occurring in the feeders. It is interesting, however, to note that for smaller breaks, quenching of the feeder wall was faster than that in the large break case i.e shorter time was needed to establish initial water-solid contact. However, it took longer time to achieve complete refilling. This is consistent with the above description. Further discussion on this phenomenon will be given later. The effect of channel power on the feeder refill time is shown in Figure 7 as well. It is shown that the channel power effect is less significant than those of the initial feeder temperature and break size.

Figures 8 and 9 show feeder refill time for the top and bottom channels in the case of parallel channel tests. These Figures suggest that there is no significant difference in complete feeder refill times for both top and bottom channels regardless of the fact that the feeders to the bottom channel are much longer than those connected to the top channel. It was found that the quenching time of the feeders connected to the top channel was always shorter than those connected to the bottom channel. Having same refilling times for both channels is believed to be caused by the strong loop interactions during the refilling process. This could be explained by the continuous venting of steam from the bottom channel loop to the top channel loop through the headers during the longer quenching time of the feeders connected to the bottom channel. This ended by the complete refilling of the bottom channel.

The effect of changing the diameter of the feeder connections to the headers from 50 mm [1] to 75 mm [2 and 3] on the feeder refill time is shown in Figures 10, 11 and 12. These Figures show that by using the larger diameter connections, the feeder refilling time was reduced. This could be explained by a possible relaxation in the flooding limitation since enlarging feeder diameter would make it easier for the steam to be vented and consequently shorter feeder refill time could be achieved.

As was mentioned earlier, the feeder refill tests reported in Ref. [4] were carried out with the uppermost horizontal section slightly inclined upward. The corresponding feeder refill times are compared with those reported in Refs. [2 and 3] with the horizontal feeder section in Figures 13, 14 and 15. It is shown that a slight increase in feeder refill time was encountered by using the upward inclined feeder section. However, this effect appears to be less dramatic than one may expect based on the results of Ref. [14] where it was shown that small upward inclination (0.6°) can cause very large reduction in the vapour velocity required to initiate flooding.

2.2.2 Propagation of Quench and Refilling Fronts in Feeders

In the previous section, the effect of various parameters on the overall feeder refilling time was given. In order to identify the basic physical processes governing feeder refilling, a detailed analysis of the propagation of the quench and refilling fronts in the feeders was carried out. The thermocouple measurements of feeder surface temperatures were used to locate the transient quench and refilling fronts along the feeders. As suggested in Ref. [15], quenching is considered to occur when a rapid decrease in the feeder surface temperature from its initial superheated value to the prevailing saturation temperature, and refilling is considered to occur when feeder surface temperature drops below the saturation temperature. The quenching and refilling times at the various temperature measurement locations, shown in Figures 5 and 6, were extracted for all refilling tests reported in Refs. [2,3 and 4] as well as selected tests from Ref. [1]. These times, which are calculated from the initiation of water injection into the headers, are presented in Appendix A. In case of an oscillatory quench-dry-quench process at various stations, the final quenching time is considered. However, before examining these extracted quenching and refilling times, a close look at typical transient temperature curves is required to characterize the local transient events associated with the process. Such transient temperature curves for a typical single (bottom) channel test is discussed below.

Typical measurements of feeder wall temperatures are given to demonstrate the nature of feeder refilling and to discuss possible implications. For this purpose, the temperature transients for a typical single channel, double break, double injection test (test no. 1408) which was reported in Ref. [4] are given. In this test, the final flow direction was from the geometrical inlet feeder to the outlet feeder.

Figure 16 gives the transient temperature curves at the bottom side of the horizontal sections of the geometrical inlet feeder (at thermocouple stations 25, 35, 27 and 41). The uppermost three thermocouples, i.e, 25, 35 and 27, show a sharp drop in temperature indicating quenching shortly after water injection while thermocouple 41 shows a delay in quenching of about 90 s after a small sudden drop in temperature. This delay could be caused by a significant counter-current steam flow upstream of this location. The thermocouple closest to the header (25) shows a temperature drop to a level lower than the saturation temperature shortly after quenching while the other three thermocouples (35, 27 and 41) show a constant temperature equal the saturation temperature for periods of about 300 s before dropping to the injected water temperature. Although the temperature of the feeder which is closest to the header (at thermocouple 25) dropped below saturation shortly after quenching, it shows continuous fluctuation in temperature for approximately 300 s before dropping down to the injected water temperature. This fluctuation could be caused by upward venting of steam to the inlet header.

Figure 17 shows the transient temperature curves for the top side of the horizontal sections of the geometrical inlet feeder (at thermocouple stations 26, 36, 28 and 42). The thermocouple closest to the header (26) shows a similar behaviour to that at the bottom side (25) shown in Figure 16. However, the delay time between quenching the bottom and top is about 24 s. The other thermocouples in Figure 17 (36, 28 and 42) do not show a distinct sudden drop in temperature but rather show gradual decrease in surface temperature which could be attributed to circumferential heat conduction from the dry top side to the wet bottom side of these horizontal sections experiencing stratified flow with slowly rising water level throughout the refilling process. The delay time between quenching the bottom and the top of the horizontal sections of the inlet feeder increased with distance from the inlet.

Figure 18 shows the transient temperature curves for the vertical sections of the geometrical inlet feeder (at thermocouple stations 39, 43, 45 and 3). The reading of thermocouple 3 which is mounted near the bottom of the inlet feeder, where the gamma densitometer was located, shows a low initial wall temperature because of heat losses (no insulation at this location) and because of the densitometer cooling. Accordingly, this reading was disregarded. The other three thermocouples (39, 43 and 45) show that the quench front propagated slowly downwards. The delay time between quenching thermocouple station 39 and that of 41 could be attributed to flooding limitation in the vertical or horizontal sections between these stations. However, the significant delay between quenching thermocouple station 43 and that of 45 suggests that the flooding limitation was also reached in the lowest vertical section.

Figure 19 shows the temperature transients at the bottom side of the horizontal sections of the geometrical outlet feeder (at thermocouple stations 31, 57, 29 and 51). The closest thermocouple to the header (31) was quenched shortly after water injection while thermocouples 57 and 29 show a small sharp drop in temperature followed by redry and requench periods indicating significant flooding and liquid flow reversal. The reading of thermocouple 51 shows that the water did not succeed in penetrating to this location for 500 s. The large fluctuations in surface temperature reflect the periodic upward venting of steam to the outlet header. The faster refilling of the inlet feeder generated a hydrostatic head directing the steam flow out of the outlet feeder also causing liquid flow reversal in the outlet feeder. Thermocouple 29, which is the closest to the outlet header, shows a sudden rise in surface temperature near the end of the transient. This can be attributed to the last period of venting superheated steam to the geometrical outlet header and liquid flow reversal in this feeder.

Figure 20 shows the temperature transient curves at the top side of the horizontal sections of the geometrical outlet feeder (at thermocouple stations 32, 58, 30 and 52). This Figure shows that thermocouple 32, which is the closest to the header, was quenched at about 30 s from the beginning of the transient while thermocouple stations 58, 30 and 52 did not quench before 500 s. Thermocouple station 58 shows a gradual temperature decrease after the bottom side of this section (thermocouple station 57) was quenched due to circumferential heat conduction from the dry top side to the wet bottom side.

Figure 21 shows the transient temperature curves of the vertical sections of the geometrical outlet feeder (at thermocouple stations 53, 49, 47 and 4). All of these locations indicate dry conditions for more than 490 s after water injection.

Comparing the readings of thermocouples 25 and 31, which are the closest to the inlet and outlet headers respectively and are also at the same location relative to the respective headers, reveals some interesting behaviour. Although the initial surface temperature of the inlet feeder was higher than that of the outlet feeder, the upper part of the inlet feeder (thermocouple 25) was quenched first. Comparing similar locations in both feeders shows clearly that, for this particular test, the quench front was able to propagate in the inlet feeder at a faster rate. As the inlet feeder was quenched and refilled first the final flow direction was from the inlet to the outlet side. The results from other tests were consistent in the sense that it was clear very early in the transient that one feeder is quenched at a faster rate and as a result the final refilling flow was from that feeder to the other.

The above observations suggest that after injecting water in the headers, water flows into both feeders. Due to steam generation produced in quenching the feeders , counter-current flow is established delaying the refilling process at various locations along the feeders. When water quenches and refills most of one of the feeders, the steam flow in the loop is totally directed to the other feeder through the channel due to the liquid hydrostatic head in the refilled feeder.

In the parallel channel tests, a refilling behaviour similar to that discussed above was observed in the feeders connected to both top and bottom channels.

2.2.3 Quenching and Refilling Propagation Curves

In this section, quenching and refilling times are estimated from the initiation of water injection to the headers. It should be noted that the transient temperature curves discussed earlier started at the beginning of the tests.

The propagation of the quenching and refilling fronts in the feeders for the typical test discussed above (test 1408) is shown in Figure 22, where the quenching and refilling times for the vertical sections and bottom side of the horizontal sections are extracted from the corresponding transient temperature curves. In case of oscillatory quenching behaviour at various locations, the final quenching time is considered. The horizontal axis of Figure 22 represents the length of feeders and channel converted to a horizontal scale. The positive and negative distances along the horizontal axis represent the geometrical inlet and outlet feeders respectively and the zero value represents the channel middle plane. This Figure shows that upon water injection to the headers, the quench front propagated into both feeders. However, the quench front in the geometrical inlet feeder reached the channel first and proceeded to the geometrical outlet feeder meeting the propagating quench front from the outlet feeder. The refilling times increased from the inlet feeder to the outlet feeder which indicated clearly that loop refilling was from the geometrical inlet feeder to the outlet feeder and suggesting that the final stages of steam venting occured through the outlet feeder to the outlet header causing a significant difference between the refilling times and quench times of the outlet feeder. This filling direction was consistent with the measured void fractions at the bottom of both feeders as well as the channel pressure drop measurements. The possible occurrence of flooding and its location along the feeders can be identified from the quench propagation curves where a delay is observed. Figure 22, accordingly, suggests the occurrence of flooding between thermocouples 27 and 39, 41 and 43 as well as 43 and 45. This implies that flooding can occur in both the horizontal or vertical sections of the feeders.

Figures 23 and 24 show a comparison between the quenching times and refilling times for two tests, conducted with 50 mm and 75 mm feeder connections to the headers. These Figures show trends similar to those found in Figure 22 where the refilling direction is from the inlet feeder to the outlet feeder and two quench fronts, one from each header, propagating into both feeders and meeting in the outlet feeder. Moreover, these Figures indicate that quenching and refilling times of the feeders with the 75 mm connections are lower than those with the 50 mm connections.

Figures 25 and 26 show the effect of feeder upward inclination on quenching and refilling times. These Figures indicate that the effect of such a small upward feeder inclination at the top horizontal section on the general characteristics of feeders quenching and refilling is small. Using the inclined feeders resulted in a slight increase in quenching and refilling times.

The effect of break size on the quenching and refilling times is shown in Figures 27 and 28. These Figures show that for the large break case loop refilling occured from the inlet feeder to the outlet feeder while for the small break case it occured from the outlet feeder to inlet feeder. However, as discussed earlier, Figure 27 indicates that in both tests quenching was initiated in the upper parts of both feeders in the early stages of the transient. Comparing quenching and refilling times of the first refilled feeder for each test shows that although the time elapsed in quenching the outlet feeder in the small break test (point a in Figure 27) is significantly shorter than that required for quenching the inlet feeder in the large break test (point b in Figure 27), the refilling time of the outlet feeder in the small break test (point a in Figure 28) is longer than that of the inlet feeder in the large break case (point b in Figure 28). This indicates that, in the small break tests, the geometrical outlet feeder was quenched and the water reached the channel in a relatively short time. However, feeder and channel refilling was significantly delayed. This delay of refilling in the small break test could be due to a slow process of vapour venting because of higher resistance to flow through the small break as well as higher system pressure for the small break as was discussed in section 2.2.1.

2.2.4 Observations on Break Symmetry Effect

As expected, all single break tests showed a very short refilling time due to the high header-to-header pressure difference. The refilling time in the double break tests was higher than that of single break tests due to the decrease in header-to-header pressure difference during the transient. In case of double but asymmetric breaks (i.e different break sizes at the inlet and outlet sides), the refilling direction was always from the side of the smaller break towards the other side. In general, under similar conditions the refilling time was reduced with increasing asymmetry reaching the minimum refilling time at the limit of a single break. However, in the large double asymmetrical breaks e.g 100/70% breaks, the reduction in refilling time from the corresponding symmetrical 100/100 break was rather negligible. This suggests that the effect of break symmetry is insignificant for break sizes above 70%. This is consistent with the results presented earlier in Ref. [1] when it was shown that the average system pressure decreased rapidly with increasing break size reaching a plateau as the break size increased above about 50%. These results are reproduced in Figure 29.

2.2.5 Refilling Direction

In the case of double break tests with near zero header-to-header pressure difference, it is of interest to establish the refilling direction. Following are some observations from the results of both single and parallel channel tests.

(a) Single Channel Tests

In the earlier refilling test series [1], all nineteen single channel tests showed that refilling occured from the outlet to the inlet geometrical feeders. This apparent prefered refilling direction was explained by the tendency of the injected water to quench and refill the outlet feeder first since its initial surface temperature was consistently lower than that of the inlet feeder. This was caused by the method of heating the test facility in which steam was injected from the inlet header down through the geometric inlet side and out through the outlet side. Temperature differences of up to 60 °C between the inlet and outlet feeders were observed at the beginning of test initiation.

However, more recent data obtained after replacing the 50 mm diameter sections in the upper parts of feeders with 75 mm diameter pipes appear to show an opposite trend. It is apparent that in single channel tests the refilling direction is not only a function of initial feeder temperature but also a function of break size and break symmetry at the inlet and outlet sides of the loop.

The single channel tests reported in the three recent reports, CWAPD-480 [2], CWAPD-481 [3], and SL-010 [4], covered the following conditions:

(i) 23 tests with equal large break size, 100% / 100% ;

(ii) 3 tests with equal small break size, 17.9% / 17.9% ;

(iii) 6 tests with equal small break size, 6.4% / 6.4% ;

(iv) 2 tests with unequal inlet and outlet breaks, 100% and 70% respectively, i.e, 100% / 70% ; and

(v) one test with unequal inlet and outlet breaks, 100% and 20% respectively, i.e, 100% / 20%.

In the large symmetric break tests, i.e, 100% / 100%, the refilling flow was established from the inlet to the outlet feeder in twenty tests while the flow was in the opposite direction in the remaining three tests. In all the tests the outlet feeder was initially at lower temperature than the inlet one. It is interesting to note, however, that in the three tests where the refilling flow was from the outlet to the inlet feeders, the initial outlet feeder temperature was particularly low (<200 °C). At such low temperature, the refilling process approaches cold refill with very low vapour generation rate which makes the outlet feeder the preferred one to be refilled first.

In the small symmetric break tests (17.9% / 17.9% and 6.4% / 6.4%), the refilling flow was always from the outlet to the inlet geometrical feeders.

In the test with 100% inlet break and 20% outlet break, the refilling flow was from the outlet to the inlet feeder. This is rather expected since the small outlet break represents a much higher hydraulic resistance to flow and consequently flowing out of the lower resistance large inlet break will be preferred. However, the two tests with inlet/outlet breaks of 100% / 70% showed refilling direction similar to the symmetric large break tests, i.e, from the inlet to the outlet feeders. This is not particularly surprising since the 70% break size is too large to cause significant additional resistance to flow as compared to the 100% break. It has been mentioned earlier that the feeder pressure decreases with break size down to a constant value for break sizes above 50%, i.e, the break size effect diminishes for break sizes larger than 50%.

The above results for single channel tests can be summarized as follows:

(i) For symmetric large break tests, the flow was predominantly from outlet to inlet in the earlier tests and from the inlet to outlet in the more recent tests obtained after the loop modifications.

(ii) If one of the feeders is particularly cold (<200 °C), it will be refilled first irrespective of other considerations.

(iii) For symmetric small break tests, the flow was predominantly from outlet to inlet.

(iv) For asymmetric large break tests (i.e, 100% / 70%), the behaviour is similar to the symmetric case. However, if one of the breaks is a small break, the feeder on the small break side is filled first and the flow is pushed out of the other feeder.

The above findings suggest that there is no unique factor controlling the refilling direction in the CWIT tests. Considering: (i) the recent tendency to first refill the inlet feeder in the large break tests although its initial temperature can be up to 50 °C higher than that of the outlet feeder, a trend which is opposite to earlier test results, and (ii)the sudden reverse in the trend for small break tests, it seems that there may be some geometric asymmetry in the loop configuration or minor differences in test procedure. It is the authers' view that for a truly symmetric case, the colder feeder should refill first. However, an argument can be developed explaining the possibility of refilling the hotter feeder first. It is known from single tube data that increasing the surface temperature results in a longer film boiling region (inverted annular flow in case of vertical tubes) which is associated with lower vapour generation rate as compared with the transition and nucleate boiling regions. Accordingly, one can argue that although the injected water is expected to quench the colder feeder first generating significant amount of vapour which will flow upward in the feeder, the hotter feeder will experience a long duration of film boiling during which the vapour generation rate is expected to be low. Counter-current flow limitation may exist delaying water flow into the colder feeder while the hotter feeder, although not quenched yet, is relatively filled with liquid in the core region. When the hotter feeder is quenched, the availability of liquid may cause fast refilling before the colder feeder is completely refilled. However, detailed examination of the data does not support this argument. Moreover, such a scenario is possible only in higher ranges of the initial feeder temperatures. This is very unlikely for initial temperatures lower than 300 °C, which is typical of the present experiments.

(b) Parallel Channel Tests

In the parallel channel tests, the subject of refilling direction is further complicated. An additional issue of interest is whether the two channels will refill in the same direction or in opposite directions. Similar trends to those in the single channel case were also observed in the parallel channel tests. Some of the characteristics were also reversed after the loop modifications.

In the earlier symmetric large break tests [1], the flow in the two channels was found to be in opposite directions in twenty-three tests out of twenty-six. In the remaining tests the flow was in the same direction in both channels (from outlet to inlet in two cases and from inlet to outlet in the third).

The more recent parallel channel results reported in Refs. [2,3, and 4] can be summarized as follows:

(i) 16 symmetric large break tests (100% / 100%), in which the flow in both channels was from inlet to outlet in 14 tests and in opposite directions in two tests

(ii) 6 symmetric small break tests (6.4% / 6.4%), where in all tests the flow in the two channels was in opposite directions.

(iii) Two tests with unequal but large breaks (100% / 70%), where the flow was from outlet to inlet in both channels.

(iv) one test with unequal breaks (100% inlet break and 20% outlet break), where the flow was from outlet to inlet in both channels.

As can be seen the trends are similar to those observed in single channel tests. It appears again that minor changes in loop geometry can result in significant changes in the system hydraulics. It is rather difficult to draw any conclusions based on a solid thermal-hydraulic theory. It is clear that the refilling characteristics of the two channels are strongly coupled since they are connected to common headers. In Ref. [16] the two parallel channels refilling in opposite directions was explained in terms of one channel refilling first venting the steam-water mixture to the corresponding outlet header and causing a pressure rise in this particular header. This in turn will drive the flow in the second channel in the opposite direction. This explanation of opposite refilling characteristics given in Ref. [16] appears to be a very reasonable qualitative description of the phenomena. However, it does not explain refilling the channels in the same direction.

2.3 Channel Refilling

The experimental results showed that the actual channel refilling time is a relatively small fraction of the overall refilling process. In most of the tests, particularly the large break tests, the channel refilling occured from one end to the other. However, in few tests, the water actually reached the channel from both ends. The channel refilling from both ends occured mostly in small break tests (6.4%/6.4%). In order to quantify the channel refilling times only tests where the channel refilling process was clearly from one end to the other were examined, i.e, tests where one feeder was completely refilled first while only the upper part of the other feeder was quenched.

The channel quenching and refilling process can be monitored by examining the temperature measurements of surfaces of individual heaters in the channel. The results showed significant stratification in the channel. The stratification length was long enough such that the bottom part of the entire channel was quenched and refilled before the upper part was quenched even at the channel inlet. In other words, the quenching of the upper part of the channel was almost by rising water level rather than axial propagation of a quench front. This is rather expected since the maximum measured flow rate into each header was about 3.0 kg/s. Only a fraction of this water is expected to flow down the feeder and through the channel while the rest is expected to flow out of the break. Accordingly, the liquid mass flux through the channel is expected to be significantly lower than 900 kg/m^2 which is the limit of stratification for refilling of hot tubes as shown in Ref. [17].

In the following analysis, the channel refilling time is the time from the complete refilling of the bottom of the actual inlet feeder (at the γ-densitometer location) to the refilling of the bottom of the other feeder (also at the γ-densitometer location). This includes not only channel refilling time but also the refilling time of the end fitting simulators and the connecting piping. The results herein are for the standard test conditions given in section 1.3.

Figure 30 shows clearly the increase of channel refilling time with increasing initial channel temperature. It also shows that the channel refilling time increases with increasing channel power. The above trends are consistent with published data even for single tubes. Figure 31 shows insignificant decrease in channel refilling time due to break asymmetry. The results also suggest that the channel refilling time is almost the same for both top and bottom channels as shown in Figure 32. Moreover, the small break tests indicated longer channel refilling times.

2.4 The Effect of Non-Condensible Gas Injection on the Refilling Process

The gas injection test program was initiated to simulate the effect of possible hydrogen generation due to the zircaloy/steam reaction on feeder and/or channel refill. Zircaloy/steam reaction can occur if the fuel sheath temperature rises to a high level.

Eight non-condensible gas injection tests were reported in Ref. [5] (report CWAPD-460). They included three single break tests where the outlet break was activated and five symmetric double break tests. Two of the single break tests and four of the double break tests were conducted with gas injection. Moreover, the results of three additional symmetric double break non-condensible gas injection tests were presented in report CWAPD-480 [2]. The break size was 17.9% in all tests and the test conditions were identical to those used in the refilling tests (i.e, 1.5 MPa injection pressure, 30°C water injection temperature, 50 kW channel power and 0.2 MPa blowdown pressure). During these tests, the non-condensible gas injection was initiated at the arrival of the injected water to the headers. The gas, either N_2 or He, was injected into the loop from six injection nozzles located one meter apart along the bottom of the pressure tube.

2.4.1 Tests of Report CWAPD-460 [5]

During these tests, the 50 mm feeder connections to the headers and 50 mm header nozzles were used. Fewer feeder surface thermocouple measurements were recorded in these tests and most of them were located at the top side of the horizontal sections. This made it difficult to trace the quenching and refilling fronts in these tests. Feeder surface temperature measurements were reported only from thermocouples No. 25, 36, 28, 42, and 3 for the inlet feeder and 32, 57, 30, 52 and 4 for the outlet feeder as indicated in Figure 6.

(a) Single Break Tests

In the single break tests, channel refilling, as indicated by the void fraction measurements, was from the inlet feeder to the outlet feeder. This was consistent with the observed positive pressure gradient between the channel inlet and outlet.

The propagation of the quench front along both the bottom and top sides of the pressure tube for these tests are shown in Figure 33 where the quenching time represents the time elapsed after water injection was initiated in the headers. This Figure shows that gas injection resulted in some delay in water arrival to the channel. However, the gas injection seems to have a negligible effect on channel quenching and refilling times. The average rewetting velocity (U) and the average time delay (τ) between quenching the bottom and the top sides of the pressure tube for theses three tests are listed below:

Test	Gas Flow (L/s)	U (m/s)	τ (s)
1261	——	0.323	20
1262	4.0 (N_2)	0.409	17.75
1263	4.3 (N_2)	0.377	21.25

The slight improvement in rewetting velocity with gas injection could be attributed to some increase of flow momentum with gas injection which can also cause some precooling of the fuel channel.

Figure 34 shows the feeder refilling times as indicated by the thermocouples mentioned in Section 2.4.1. This Figure shows a slight increase in the refilling times with gas injection. This increase in refilling times is more obvious in the outlet feeder, indicating that most of the injected gas in the single break tests was directed to the outlet feeder.

Based on the above, it can be concluded that non-condensible gas injection has little effect on the rewetting time and on the peak surface temperature in the single break case.

(b) Double Break Tests

In the double break tests, the header to header pressure difference was negligibly small. Accordingly, the injected gas in the channel could be divided to flow upwards through the two feeders causing a delay in refilling both feeders.

The quench front propagation along the bottom and top sides of the pressure tube during the double break tests, included in Ref. [5], is shown in Figure 35. The 2 L/s gas injection tests are not shown in Figure 35 since water failed to propagate down to the channel during these tests. The average rewetting velocity (U), obtained by averaging the rewetting velocities at the top and bottom of the channel, and the time delay (τ) between quenching the bottom and the top sides of the pressure tube for the double break tests are listed below:

Test	Gas Flow (L/s)	U (m/s)	τ (s)	Channel Refilling
1258	——	0.0802	233	yes
1260	1.05 (N_2)	0.0548	234	yes
1265	1.05 (N_2)	0.0758	231	yes
1259	2.0 (N_2)	——	——	no
1264	2.0 (He)	——	——	no

It is clear from Figure 35 that similar to most double break tests the quench front propagated along the bottom of the channel until the channel bottom side was completely quenched. The upper part of the channel was then quenched by the rising water level. Figure 35,however, shows differences in the arrival time of the injected water to the channel which is certainly related to the feeder refilling characteristics. In tests No. 1258 and 1260 the initial feeder temperatures were about 260 °C while the initial feeder temperature in test No. 1265 was lower by about 15 °C. In examining the water arrival times shown in Figure 35, tests No. 1258 and 1260, having similar initial feeder temperature, are compared. It is clearly seen that injecting the non-condensible gas in test 1260 resulted in significant delay (about 90 s) in water arrival to the channel as a result of delaying feeder refilling. In case of test 1265, the delay due to gas injection was almost compensated for by the colder feeder. Having a colder feeder is expected to decrease the feeder refilling time since it is associated with lower vapour generation rate during quenching, i.e, lower steam rise velocity in the feeder. The effect of feeder initial temperature on the water arrival time to the channel can be seen by comparing the results of tests 1260 and 1265 in Figure 35.

Comparing the results of the double break tests with those of single break tests shows that quenching the bottom side of the channel in the double break tests started after more than 220 s of initiating water injection in the header while it started at less than 52 s in the corresponding single break tests. This shows clearly that there was a significant delay in feeder refilling in the double break tests. Moreover, the double break tests show a significant increase in the time delay between quenching the bottom and the top side of the pressure tube (less than 22 s in the single break tests and more than 230 s in the double break tests). This indicates a significant increase in water stratification in the double break tests. It is clear that in the double break tests water flow to the channel was limited by feeder flooding. The decrease in water flow to the channel resulted in a significant increase in water stratification. Accordingly, channel refilling occured by rising water level after quenching the bottom side of the channel. This is evident from Figure 35 since the bottom side of the channel quenched in about 50 s while the delay between quenching the bottom and the top sides was more than 200 s.

Figures 36 and 37 show feeder quenching and refilling times for tests 1258, 1259 and 1260. Figure 36 shows that injecting 1.05 L/s of N_2 resulted in a slight delay in quenching the outlet feeder (which was filled first in this test). Moreover, increasing the gas injection rate to 2 L/s completely prevented water penetration such that water propagated from the headers for only a small fraction of the feeder length. Figure 37 shows that injecting 1.05 L/s of N_2 resulted in a delay in the outlet feeder (the feeder refilled first) refilling. However, the test appears to have been terminated before the complete refilling of the inlet feeder. Moreover, the 2 L/s N_2 injection test indicated no complete refilling at any section of the feeders. Injection 2 L/s of He (test 1264) instead of N_2 showed similar behaviour of establishing a complete carry over of the injected water in the feeders and the channel was dry until the test was terminated.

2.4.2 Tests of Report CWAPD-480 [2]

Three double break non-condensible gas injection tests were reported among the feeder refilling series of tests reported in Ref. [2]. In these tests, the 75 mm feeder connections to the headers and the 75 mm header nozzles were installed. More detailed temperature measurements along the feeders (all thermocouples shown in Figure 6) were obtained during these tests. N_2 gas was injected at a rate of 1.2 L/s in two tests (tests 1284 and 1285) and at a rate of 2.2 L/s in the third test (test 1288). In all these three tests the injected water failed to reach down to the channel. Figures 38, 39, 40, 41, 42 and 43 show the transient temperature curves for test 1286 at the various thermocouple locations, shown in Figure 6. These Figures are discussed below.

Figure 38 shows the temperature curves at the bottom side of the horizontal sections of the inlet feeder. This Figure indicates that the locations of thermocouples 25 and 35 were quenched and refilled early in the transient. The location of thermocouple 27 was also quenched shortly after. However, it is shown that at this location dryout was encountered again, suggesting the occurrence of flooding, for about 130 s before it was requenched again. Thermocouple 41 shows a dry condition until about 480 s after the test initiation.

Figure 39 shows the temperature curves for the top side of the horizontal sections of the inlet feeder. This Figure shows that the closest thermocouple to the inlet header was quenched shortly after water injection to the header while the other three thermocouples show continuous dry conditions indicating that these horizontal sections were never refilled during the test. The gradual temperature decrease shown in these curves is a result of heat loss during the process. This gradual temperature gradient became steeper after the bottom sides of these sections were quenched due to circumferential heat conduction from the dry top side to the wet bottom side of the horizontal feeder sections.

Figure 40 gives the temperature curves for the vertical sections of the inlet feeder. These curves indicate that the quench front propagated down the feeder at a very slow rate such that it reached thermocouple

3, where the gamma densitometer was located, in more than 700 s.

Figure 41 shows the temperature curves for the bottom sides of the horizontal sections of the outlet feeder. It is clearly shown that while the upper two locations were quenched at about 50 s, the other two locations (at thermocouples 29 and 51) were dry during the test. This indicates, that during the entire test, water could not penetrate even to thermocouple 29.

Figure 42 shows the temperature curves for the top sides of the horizontal sections of the outlet feeder. This Figure indicates that the closest location was quenched shortly (50 s) after water injection to the header while the other three locations were dry during the entire test. However, thermocouple 58 shows a faster cooling rate than the other two thermocouples (30 and 52) due to the effect of circumferential heat conduction from the dry top side to the wet bottom side at this location. This also indicates that even the upper horizontal section of the outlet feeder, where thermocouples 57 and 58 were mounted, was not refilled during the entire test.

Figure 43 shows the temperature curves for the vertical sections of the outlet feeder. This Figure confirms that these sections were not quenched during the entire test. Thermocouple 4 indicates a faster cooling than the other thermocouples since the feeder was not insulated at this station and was affected by cooling the gamma densitometer at this location.

The feeder quenching times for the three tests 1284, 1285 and 1286 are shown in Figure 44. In this Figure, the quenching time is estimated from the time of initiation of water injection to headers. This Figure indicates that although the water did not reach the channel in all these three tests, it reached a location close to the bottom of both feeders in tests 1284 and 1285 (i.e for gas injection rate of 1.2 L/s) and the bottom of the inlet feeder in test 1286 with 2.2 L/s gas flow rate. Accordingly, it appears that the water would have eventually reached the channel if the heater elements could sustain the temperature rise without failure. However, the refilling delay time was significantly high. Figure 44 shows that although the gas injection rates were similar during tests 1284 and 1285, the quenching times of test 1284 was significantly higher. This could be attributed to the difference in feeder temperature. The initial feeder temperature in test 1284 was about 30 °C higher than that in test 1285 which could result in a higher vapour generation and accordingly a more restrictive flooding limitation.

It should be noted that the low gas injection double break tests reported in Ref. [5] (tests 1260 and 1265), showed refilling times significantly lower than those reported in Ref. [2] (tests 1284 and 1285). This could be attributed to the higher gas injection rate (1.2 L/s in tests 1284 and 1285 while 1.05 L/s in tests 1260 and 1265) and the higher initial feeder temperatures (ranging between 262 to 330 °C in tests 1284 and 1285 while ranging between 245 to 290 °C in tests 1260 and 1265) encountered in the tests reported in [2]. The above seem to over compensate the expected relaxation of the flooding criterion in the later tests where larger diameter section of the feeders were used (75 mm instead of 50 mm). Further work is needed to confirm the above statements.

2.4.3 Analysis of Feeder Flooding

The above analysis shows that flooding can be encountered in different sections of the feeders. Moreover, non-condensible gas production in the channel can result in reaching the liquid carry-up limit in the feeders where water cannot penetrate down to the channel for a significant period of time. Although the gas injection rates used in the above tests appear to be relatively low to cause the observed carry-up limit in the feeders, its combined effect with the rising steam, generated in quenching the feeders, may possibly result in reaching the carry-up condition.

Significant studies on the onset of flooding and the carry-up limit were reported in Refs [14,18 and 19]. It was found that the gas flow velocities required to initiate flooding in a horizontal pipe near an elbow connection to a vertical section were well below those expected to initiate flooding in vertical pipes. As a result, the horizontal sections in the feeders may be seen as the most critical sections. The present results show that flooding in the feeders can also occur in the vertical sections. In Ref. [14], the onset of flooding in a circular horizontal pipe near a pipe bend was correlated by

$$j_G^* = 0.2\ \alpha^{3/2} \qquad (1)$$

where j_G^* is the nondimensional volumetric flux of the gas phase defined by

$$j_G^* = \frac{j_G}{(g\ D\ [\rho_L - \rho_G]/\rho_G)^{1/2}}$$

In the above equations D, α, ρ_G, ρ_L and j_G are the tube diameter, void fraction, vapour density,
liquid density and superficial gas velocity, respectively. Moreover, the complete flooding (carry-up limit) was found in Ref. [4] to occur at

$$j_G^* = 0.2025 \qquad (2)$$

In order to investigate the applicability of the above correlations (equations 1 and 2) and to examine the flooding characteristics in the feeders of the CWIT test facility, it is important to estimate the nondimensional volumetric gas flux j_G^* at which flooding was encountered in the feeders during the tests. The validity of equation 1 cannot be assesed by the present data since the void fraction measurement at the flooding location is not available. However, j_G^* which caused the carry-up limit observed in the double break non-condensible gas injection tests with gas injection ≥ 2 L/s can be estimated approximately as follows:

The injected gas is assumed to split equally between the two feeders with each half venting through one feeder. This can be justified by the near-zero pressure difference between the feeders and because both feeders experienced extensive flooding limitations. Accordingly, the gas flow in each feeder would be about 1 L/s at standard temperature and pressure (300 °K, and 0.1 MPa). Using the ideal gas assumption, the corresponding nitrogen mass flow rate in each feeder is 0.00113 kg/s.

Assuming that the injected gas would be at the feeder conditions (0.3 MPa absolute pressure and around 250 °C), the superficial gas velocity in the smallest cross section of the feeders (50 mm diameter) is 0.296 m/s. This velocity corresponds to non-dimensional volumetric flux of $j^*_{G(N2)} = 0.0186$. This value of the nondimensional volumetric flux of the injected N_2 is significantly lower than the carry-up limit given by equation (2). It could be argued that the combined flow of gas and steam, which was generated during quenching, was responsible for the carry-up limit encountered in the double break non-condensible gas injection tests. Therefore an estimate of the nondimensional volumetric flux of the mixture of the injected gas and the generated steam j^*_m is required. This requires the knowledge of the steam flow rate which in turn requires an estimation of the vapour generation rate. An approximate method for the estimation of steam flow is used herein following the work reported in Ref. [20].

The flooding limit in an elbow was approximated in Ref. [18] by

$$j_S^{*1/2} = 0.447 - 0.176\, j_L^{*1/2} - 0.263\, j_L^* \qquad (3)$$

where j^*_S and j^*_L are the dimensionless volumetric flux of steam and water at the onset of flooding, respectively. Assuming that all the downward liquid flow is converted to steam at the flooding limit, one can write the equation

$$j_S \rho_S = j_L \rho_L \tag{4}$$

where j_S and j_L are the superficial steam and water velocities respectively. Using the definition of j^*, equations (3) and (4) can be solved to yield $j_S^* = 0.1847$ or $j_S = 3.067$ m/s.

Now, the mass fraction of the non-condensible Nitrogen gas in the mixture is defined as,

$$x_G = \frac{M_G}{M_G + M_S} \tag{5}$$

which yields $x_G = 0.1015$

Defining the gas and steam mixture density as,

$$\rho_m = \rho_S (1-x_G) + x \rho_G \tag{6}$$

we get,

$\rho_m = 1.64$ kg/m^3 for the mixture of N_2 and steam

Now defining j_m and j_m^* as,

$$j_m = \frac{Ms + MG}{\rho_m A} \quad \text{and} \quad j_m^* = \frac{j_m}{[g\ D\ (\rho_L - \rho_m)/\rho_m]^{0.5}}$$

This results in $j_m = 3.43$ m/s and $j_m^* = 0.1989$. Similar calculations were made for the Helium injection tests resulted in $j_m = 3.24$ m/s and $j_m^* = 0.1848$. This indicates that although the steam counter-current flow was overestimated by assuming that all vapour generated flows opposite to water, the predicted non-dimensional volumetric flux of the mixture of gas and steam, which caused the carry-up limit, is lower than that suggested by equation (2).

It should be noted that flooding can occur in two ways. The first is by injecting the counter-current gas flow against an established downward liquid flow (liquid first flooding). The second type can occur by injecting the liquid flow against an established upward gas flow (gas first flooding). It is expected, that gas first flooding is more limiting than liquid first flooding. The flooding limitation occured during the tests of the CWIT test facility is a gas first flooding since gas injection and upward steam flow started before feeder refilling was initiated while the carry-up limit correlation, given by equation (2), was obtained from liquid first tests. Accordingly, in the CWIT tests, lower values of steam and gas flows can cause the carry-up limit. Another possible reason for the apparent more restrictive flooding criterion in the CWIT experiments can be due to the complexity of the feeder geometry.

It should be also noted that the quench front propagation is self limiting, such that faster quench front propagation will result in higher vapour generation rate which will limit the liquid penetration resulting in reduction of the vapour generation rate, and so on. However, in the gas injection tests, where the carry-up limit was experienced, it seemed that the quench front was halted at certain location for a long time. If the counter current steam flow is the most dominant factor in causing flooding, it is expected that the quench front would propagate again as a result of the decrease in steam generation and the corresponding relaxation of flooding particularly after cooling the quenched portion of the feeder. This suggests that the relatively small amount of gas injection in the double break tests has probably played an important role in reaching the flooding and carry-up limits. This also supports the trend that the carry-up limit in this complex feeder geometry is significantly lower than that suggested by equation (2).

The above uncertainty could be solved by conducting cold refilling tests in the feeder geometry, with gas injection, to investigate the actual gas carry-up limit in the absence of steam generation.

2.5 Flow Stratification in the Fuel Channel

2.5.1 The Tests

Special tests (1154 to 1181) were reported in Ref. [6] (CWAPD-433) which were specifically aimed at examining the onset of flow stratification in fuel channels using the CWIT test facility. Only the bottom channel was used in these tests and the pressure tube was insulated. The inlet header break line was completely closed and the exit header break line was fully opened while water was injected into the inlet header only, i.e, the water was directed in an open loop from the inlet header through the channel and out of the outlet header to the blowdown tank. Preheated water was circulated through the loop, where a uniform temperature was attained throughout the loop, the required injection and blowdown pressure, were established. The power level to the fuel string was increased in steps maintaining constant water flow rate until flow stratification was initiated. The onset of flow stratification was identified when the thermocouple attached to the top heater element at the channel outlet indicated an above saturation temperature.

Twenty eight tests were carried out for different flow rates, inlet subcooling and system pressure. The channel power at the onset of stratification was recorded.

2.5.2 Data Analysis

As may be expected, the channel power required to initiate flow stratification at the outlet of the channel increased with increasing flow rate, inlet subcooling and system pressure. However, it is well established that flow regime transition is a local phenomenon and accordingly, the data was reduced to calculate the local conditions corresponding to the onset of stratification. Assuming equilibrium thermodynamics, the exit local quality and superficial liquid and vapour velocities were calculated. The onset of flow stratification data in terms of liquid and vapour superficial velocities for different system pressures is shown in Figure 45.

The results were compared with the flow regime transition criterion used in the CATHENA code as given in Ref. [21]. In CATHENA only two flow regimes in horizontal channels are used, namely stratified and mixed flows. The flow regime transition criterion is employed in such a way to remove the discontinuities in constitutive relationships between the stratified and mixed flow regimes. Accordingly a transition region between the stratified and mixed flow regimes is established in which all parameters are averaged using linear weighing function between the truly stratified and mixed values. The criterion used to relate the superficial phase velocities is given below,

$$j^{+} = j_{L} / (0.8004\ \phi) \qquad (7)$$

where

$$\phi = D_{e}^{0.4543} \qquad \text{for } j_{G} < 1$$

$$= D_{e}^{0.4543}\ j_{G}^{0.0909} \qquad \text{for } j_{G} \geq 1$$

In the above equations, if $j^{+} < 1$ the flow is assumed completely stratified, while if $j^{+} > 10$ it is assumed completely mixed. In the range $1 < j^{+} < 10$, the flow interfacial parameters are averaged between the two regimes using a simple weighing function.

The above boundaries for flow through the fuel channel are superimposed on Figure 45. It is shown that the experimental data falls mostly in the transition zone and are particularly close to the stratified transition line (note the Log-Log scale). Based on these findings, it is believed that the above transition criterion used in the CATHENA code is fairly satisfactory.

C. CATHENA CODE

1. The Code

CATHENA is a one-dimensional thermal-hydraulics code developed by AECL-WNRE for thermal-hydraulics analysis in nuclear reactors during LOCA. The code was developed based on a two-fluid model. Six conservation equations, describing the conservation of mass, momentum and energy for each phase, are used. The conservation equations are complemented by a set of constitutive equations describing the interfacial and wall transport processes. The constitutive equation set used is flow regime dependent. Two possible flow regimes are assumed, namely, separated and mixed flow regimes. The code can handle a wide variety of one-dimensional problems involving thermal and hydrodynamic non-equilibrium.

The predictions of CATHENA code were compared with experimental results obtained from two CWIT tests and one RD-14 test. The results are discussed below.

2. Comparison with Data

2.1 CWIT Test 774

This is a single break single channel test reported in Ref. [22]. The break size was 6.3% and located at the geometrical outlet header. The injection pressure was 2.0 MPa and the injection water temperature was 30 °C. The blowdown pressure was 0.1 MPa and the channel power was 300 kW.

Figure 46 shows the measured inlet header pressure transient and the corresponding CATHENA code predictions. It is shown that CATHENA predictions are in good agreement with the experimental results. The quick depressurization down to about 500 KPa followed by a pressure increase to about 2 MPa was well predicted.

Figure 47 shows the corresponding transient flow rate into the inlet header. It is clear that the code predictions compare very well with the experiment. The initial increase in water flow corresponds to the initial depressurization period shown in Figure 46.

The transient void fraction near the bottom of the inlet and outlet feeders is presented in Figure 48. The experimental and code prediction results are shown in Figures 48a and 48b respectively. Good agreement between the experimental results and code predictions is evident. The code predicted a slightly longer time delay for the refilling front to move from the bottom of the inlet feeder to the outlet feeder.

Figure 49 shows the transient temperature curves for a top and a bottom pins at 4.75 m from the channel inlet. Again, it is clear from this Figure, that the CATHENA code predictions are in reasonably good agreement with experimental data. The stratification effects causing the delay in quenching the upper pin are clearly well predicted.

Figure 50 shows the transient temperature curves for a top pin at 0.5 m and 5 m from channel inlet. Also this Figure shows the ability of the CATHENA code in predicting channel refilling in this test.

2.2 CWIT Test 1098

This is a symmetric double break test with zero channel power which was reported in Ref. [1]. The break size was 1%. The injection pressure was 1.5 MPa and the blowdown Pressure was 0.2 MPa. At the end of this particular run, the refilling flow was established from the outlet geometrical feeder to the inlet one.

The inlet and outlet header pressure transients obtained from the experimental data and CATHENA predictions are presented in Figure 51. Both indicate a depressurization period, followed by a sharp increase of pressure. However, the experimental results indicate a maximum pressure near 1.5 MPa while the code predicted a value of about 2 MPa. In the experimental results, this pressure increase is followed by a slight reduction in pressure, and then the pressure fluctuated around a constant value of about 1.3 MPa. The code, however, predicted a sharper drop in pressure down to about 0.75 MPa followed by a sharp rise to a value of 1.4 MPa. The predicted pressure fluctuations that followed were of higher amplitude than those observed in the experimental results. The second header depressurization predicted by CATHENA could be attributed to overprediction of vapour condensation after injection initiation.

The water injection flow rates into the inlet and outlet headers are given in Figure 52. The correspondence between the flow rates into the headers and the transient pressures in the headers is clear for both the experiment and code predictions. At break initiation, water flow rate increased sharply to about 3 L/s. However, additional flow fluctuations and a period of negative flow into the inlet header were predicted by the code.

Figure 53 shows the transient void fractions near the bottom of the inlet and outlet feeders. The general sequence of refilling is well predicted by CATHENA. Both the experimental results and CATHENA code predictions show that both feeders are refilled initially but the inlet feeder was voided again for a long period before it was finally refilled. However, the refilling time was overpredicted by CATHENA. The initial feeders refilling occured at 140 s while the inlet feeder was completely refilled at 380 s. The corresponding predicted times were 180 s and 520 s.

Figure 54 shows CATHENA predictions of water and vapour velocities at the bottom of the inlet feeder near the void fraction measurement location. In this Figure, the positive values represent downward velocities in the inlet feeder towards the channel. It is clear that vapour attained significant upward velocities between 280-500 s as it was vented out of the inlet feeder by the hydrostatic pressure difference. This is consistent with the void fraction prediction of Figure 53b where it showed near complete voiding for the same period (280 - 500 s).

The inlet feeder surface temperature at the same location (where Gamma densitometer was located) is shown in Figure 55. The code prediction is consistent with the void fraction predictions such that after near refilling (180 -280 s), where the feeder temperature was below saturation, the predicted temperature increased to near saturation during the period 280 - 500 s, which suggests that a flow of two-phase mixture replaced the single liquid flow. However, the experimental curve in Figure 55a does not show a refill period at any stage but it shows that the inlet feeder, at this location, was almost at saturation temperature after initiating quenching at about 100 s from the start.

The experimental results and CATHENA predictions of the outlet feeder temperature, where γ-densitometer was located are given in Figure 56. This Figure also indicates that CATHENA overpredicts the quenching and refilling times at this location by about 20 s and 90 s respectively.

2.3 RD-14 Test B8603

A brief overview of RD-14 channel refilling results is presented in Appendix B. The following is a comparison between the predictions of the CATHENA code and the results of a typical small break RD-14 experiment.

RD-14 B8603 is a small inlet header break test conducted in RD-14 test facility and was reported in Ref. [23]. The break diameter was 7 mm, which scales to the cross sectional area of two feeders for a CANDU reactor LOCA. The break was located at the inlet header 4. Unlike the CWIT experiments, this test started from the steady state conditions of full power (5 MW per pass), full flow (21 kg/s), and nominal reactor outlet header pressure (10 MPa). The secondary side pressure was set to 4.5 MPa and the emergency coolant injection (ECI) system was set to 5.5 MPa for the high pressure ECI and 1.3 MPa for the low pressure ECI. In this test, the surge tank was isolated 4 s before break initiation, and the power was triped 20 s after break initiation.

Figures 57 - 60 show the transient pressure curves for the four headers. Figures 61 and 62 show the transient flow rate at the inlet of both channels. Figures 63 - 66 show the transient temperature curves for a top and a bottom pins in the two heated channels.

All above Figures show good agreement between the experiment and code predictions.

D. CONCLUSIONS AND RECOMMENDATIONS

1. Concluding Remarks

1.1 CWIT Experiments

(i) The experimental data on feeder/channel refilling obtained using the CWIT facility were analysed. Analysis of the data showed clearly that following a single break, the refilling process is accomplished in a relatively short period of time with co-current steam-water flow venting out of the break. The single break case is well predicted using existing analytical tools.

(ii) In the double break case, where near zero header to header pressure difference may exist, the feeder/channel refilling is more complicated with the possibility of counter-current steam-water flow occurring throughout the loop causing possible refilling delay. Based on the extensive data obtained from the CWIT facility for the double break case, the following conclusions can be made:

- The overall refilling process is controlled by feeder refill. Significant refilling delay can be encountered due to steam-water counter-current flow limitation in the feeder (CCFL).

- During the initial stages of the transient, with near zero header to header pressure difference, the quenching and refilling fronts advance down both feeders. Due to minor asymmetry, the injected water tends to advance at a faster rate down one of the two feeders establishing a hydrostatic head that forces the two-phase mixture out through the other feeder where flow reversal is encountered. Accordingly, the final refilling flow direction is established. A feeder having a particularly low initial wall temperature (< 200 °C) tended to be refilled first.

- During feeder refill, CCFL can take place in both horizontal or vertical sections of the feeders i.e no clear critical section seems to exist.

- The overall feeder refilling time appears to increase with increasing initial feeder wall temperature, decreasing break size below 50%, increasing channel power, decreasing feeder size or having upward inclination of the horizontal feeder sections. Feeder refilling time was also found to decrease with increasing asymmetry of break sizes reaching a minimum value at the limit of single break. This effect was found to be important when the smaller break is less than 50%. In the parallel channel case, similar feeder refilling times were observed for both the top and bottom channels reflecting the strong interaction between the two channels which are connected to common headers.

- Channel refilling can take place in either direction depending on which feeder is refilled first. Water arrival to the channel can be delayed due to CCFL in the feeders but once a feeder is refilled, the water is driven through the channel by hydrostatic pressure forces.

- Within the range of experimental conditions tested, significant stratification was observed during channel rewetting and refilling. The process approached refilling by a rising water level rather than an advancing refilling front.

- The channel refilling time increased with increasing initial channel temperature and channel power.

(iii) Experiments were also carried out to investigate the effect of non-condensible injection on the refilling process. Analysis of the single break test results showed that the effect of non-condensible gas injection on the refilling time and on the peak surface temperature is negligible. However, for the double break tests, the results showed that non-condensible gas injection can cause significant refilling delay. Within the range of test conditions covered in the present data, the injected water failed to penetrate to the channel reaching the complete carry-up limit for gas injection rates ≥ 2 L/s. Approximate analysis was carried out to estimate flooding and carry-up limits in the feeders. It is apparent that the gas velocities required to reach both limits in a CANDU feeder geometry are lower than the values predicted by available correlations.

(iv) Tests were also carried out to examine the onset of stratification in the fuel channel with an initially filled loop. The data was reduced to the local flow parameters at the onset of stratification. It was shown that current criteria used for flow regime transition to stratified flow are adequate.

1.2 CATHENA Code

The CATHENA code was used to simulate three types of tests: a single break CWIT test, a double small break symmetrical CWIT test and a small break RD-14 test. In general, the code predictions showed good agreement with the experimental results.

2. RECOMMENDATIONS

(i) To complete the analysis of available CANDU related refilling data, it is recommended that detailed analysis of the RD-14 refilling data be carried out.

(ii) The evaluation of the CATHENA code need to be extended to the simulation of other types of tests, which were covered in the present work. These include three CWIT tests: a double large break test, an asymmetric break test and a refilling test with non-condensible gas injection. Moreover, the simulation of a large break RD-14 test needs to be carried out.

(iii) Since it is apparent that the refilling process is very sensitive to non-condensible gas injection, it is recommended that the CWIT facility be used to conduct a series of cold refilling tests with non-condensible gas injection.

(iv) The results of the present work suggest that the refilling process is controlled by the feeder refilling characteristics. It was also shown that current correlations, developed from data obtained for simple geometries, are inadequate in predicting the onset of flooding and carry-up limits in feeder geometry. Accordingly, it is recommended that detailed flooding experiments be carried out using a scaled-down feeder geometry (1:2) made of transparent pipes. The use of air-water flow is recommended for these experiments so that detailed flow visualization can be made. this program should provide important information on :

- Onset of flooding and carry-up limit in a true feeder geometry which appear to be different from the simple geometries such as tubes and bends.
- The existence of a "critical section" in CANDU feeders.
- The difference between liquid first and gas first flooding.

(v) To complement the above recommended studies, there is a need to study the processes of hot feeder rewetting. Therefore, it is recommended that experiments be carried out on top rewetting and refilling of hot tubes with simultaneous counter-current steam flow. These experiments will provide important information on feeder cooling limited by flooding. It is also recommended that these experiments be first carried out using electrically heated vertical tubes which can then be extended to include more complex geometries. Tests including simultaneous non-condensible gas injection can also be carried out in such a program.

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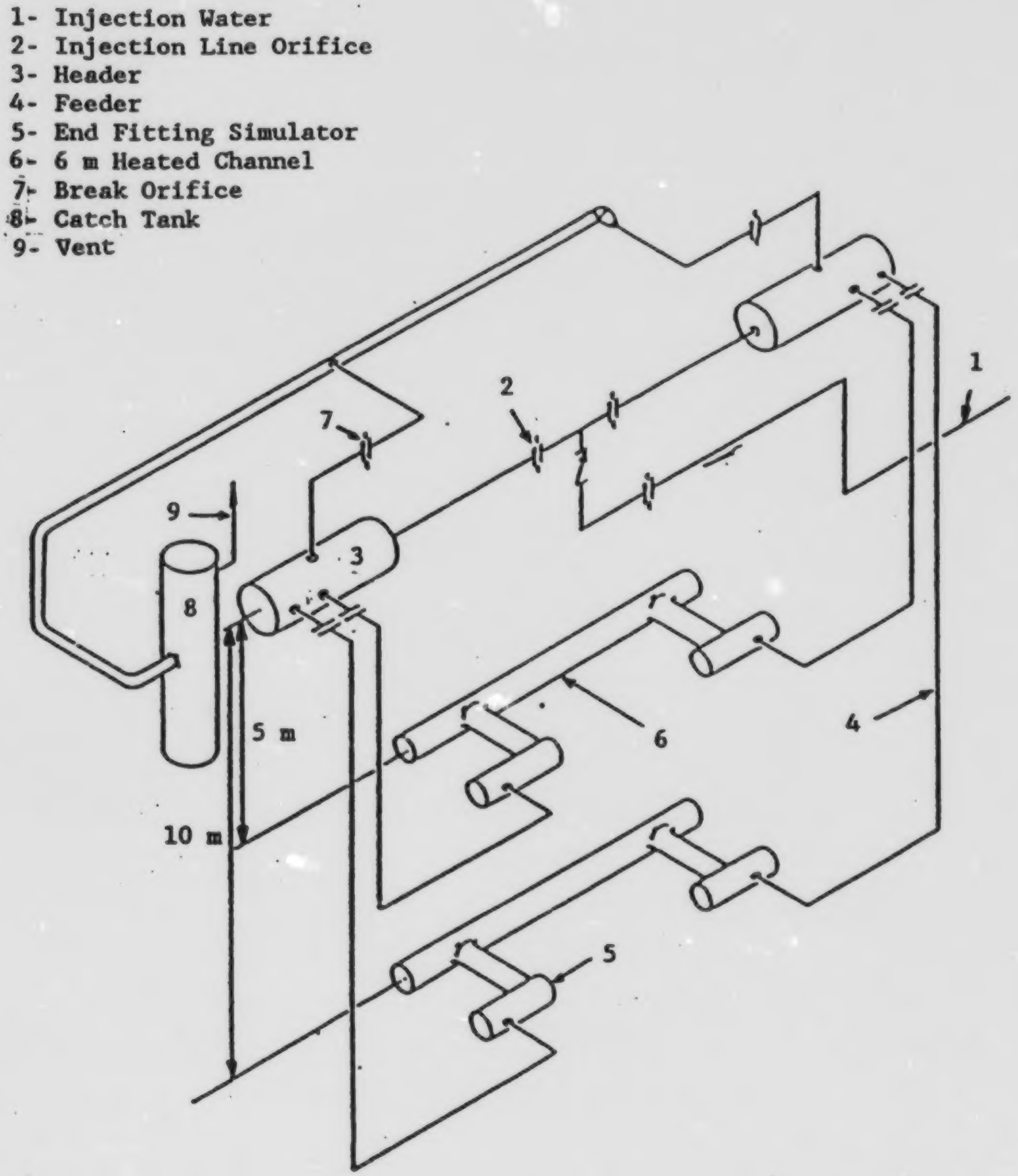

1- Injection Water
2- Injection Line Orifice
3- Header
4- Feeder
5- End Fitting Simulator
6- 6 m Heated Channel
7- Break Orifice
8- Catch Tank
9- Vent
1
2
7
9
3
8
5 m
10 m
6
4
5

FIGURE 1: SCHEMATIC OF CWIT EXPERIMENTAL TEST FACILITY

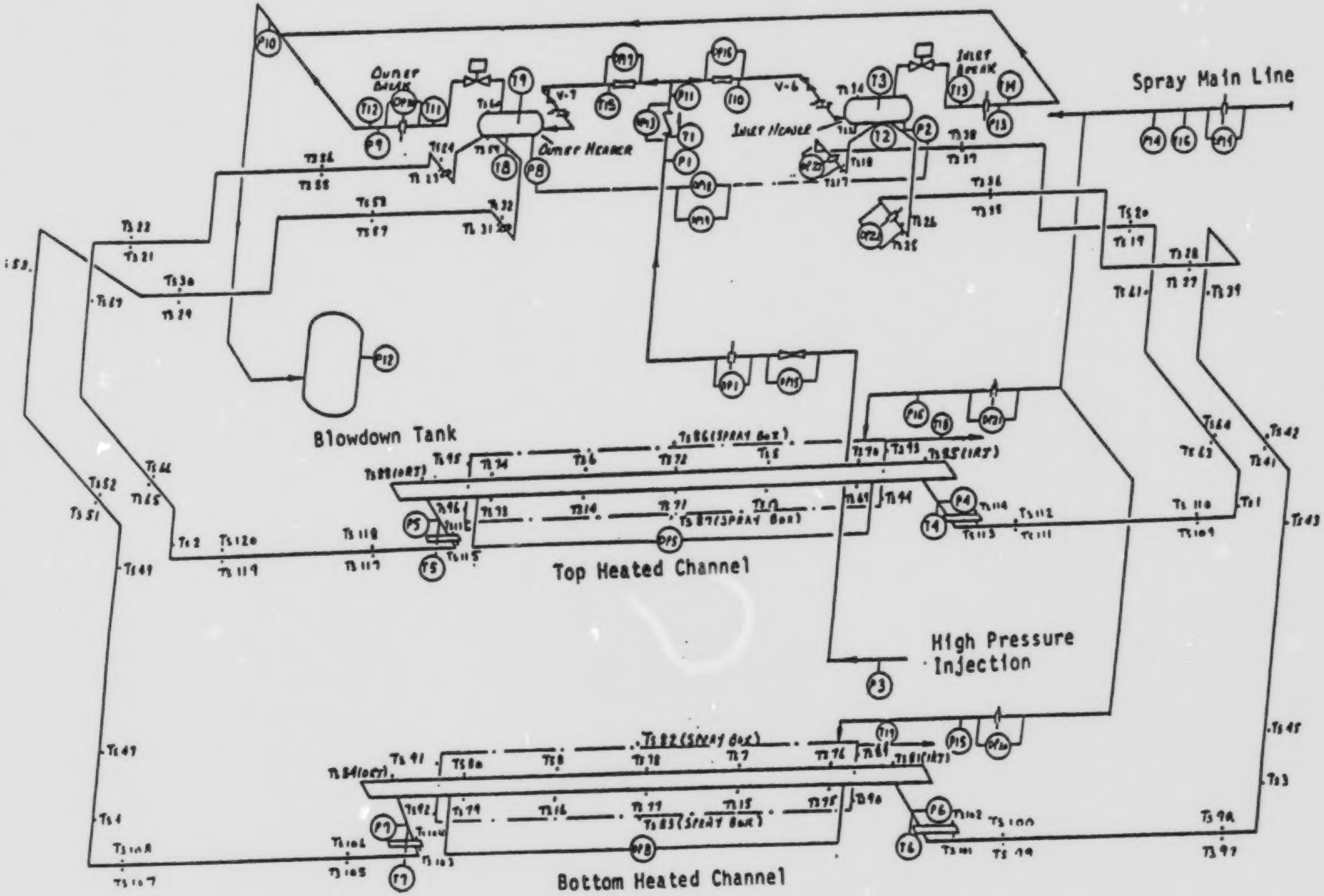

Spray Main Line
Outlet Break
Inlet Break
Outlet Header
Inlet Header
V-7
V-6
Blowdown Tank
Top Heated Channel
High Pressure Injection
Bottom Heated Channel
P10
P12
P3
TS86(SPRAY BOX)
TS87(SPRAY BOX)
TS82(SPRAY BOX)
TS83(SPRAY BOX)

FIGURE 2: CWIT LOOP INSTRUMENTATION

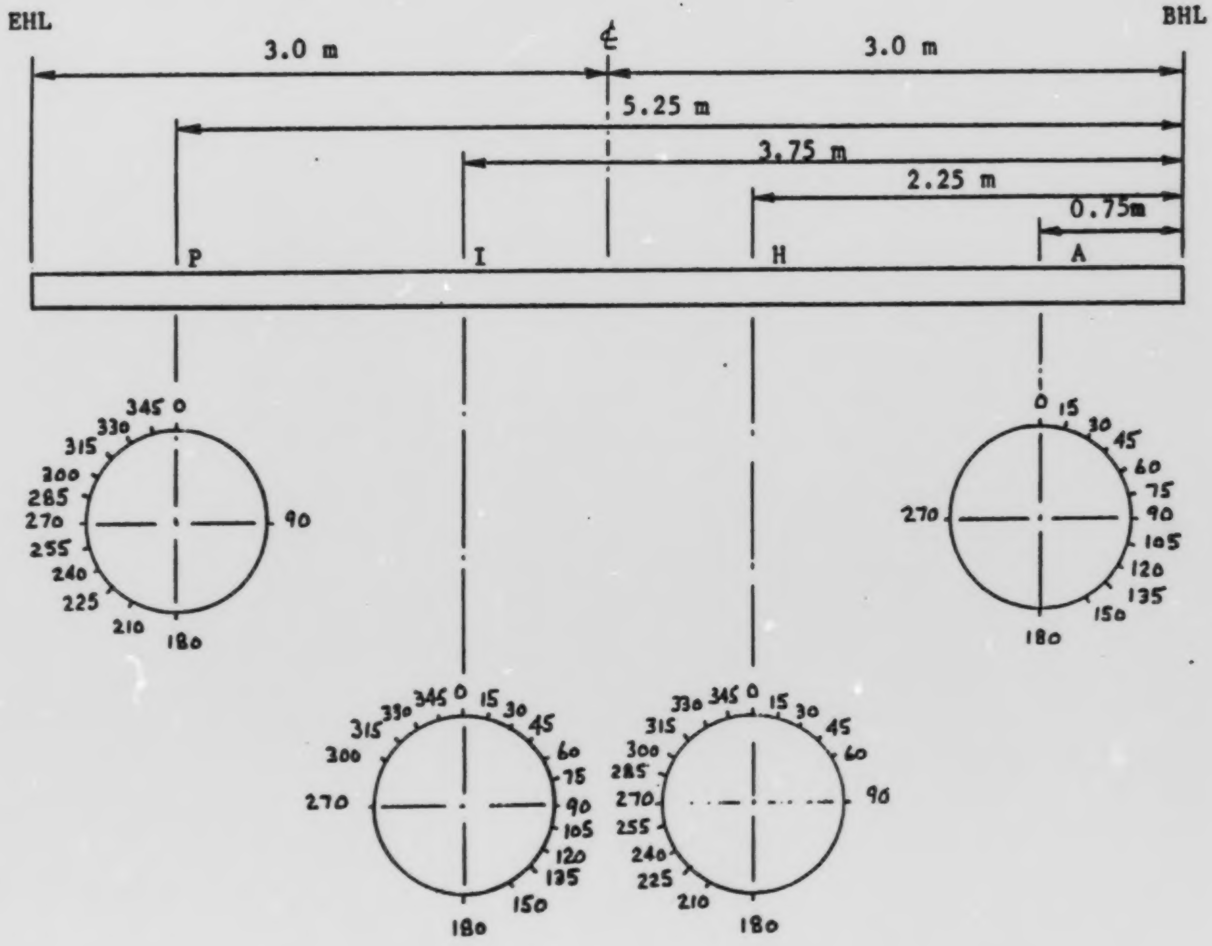
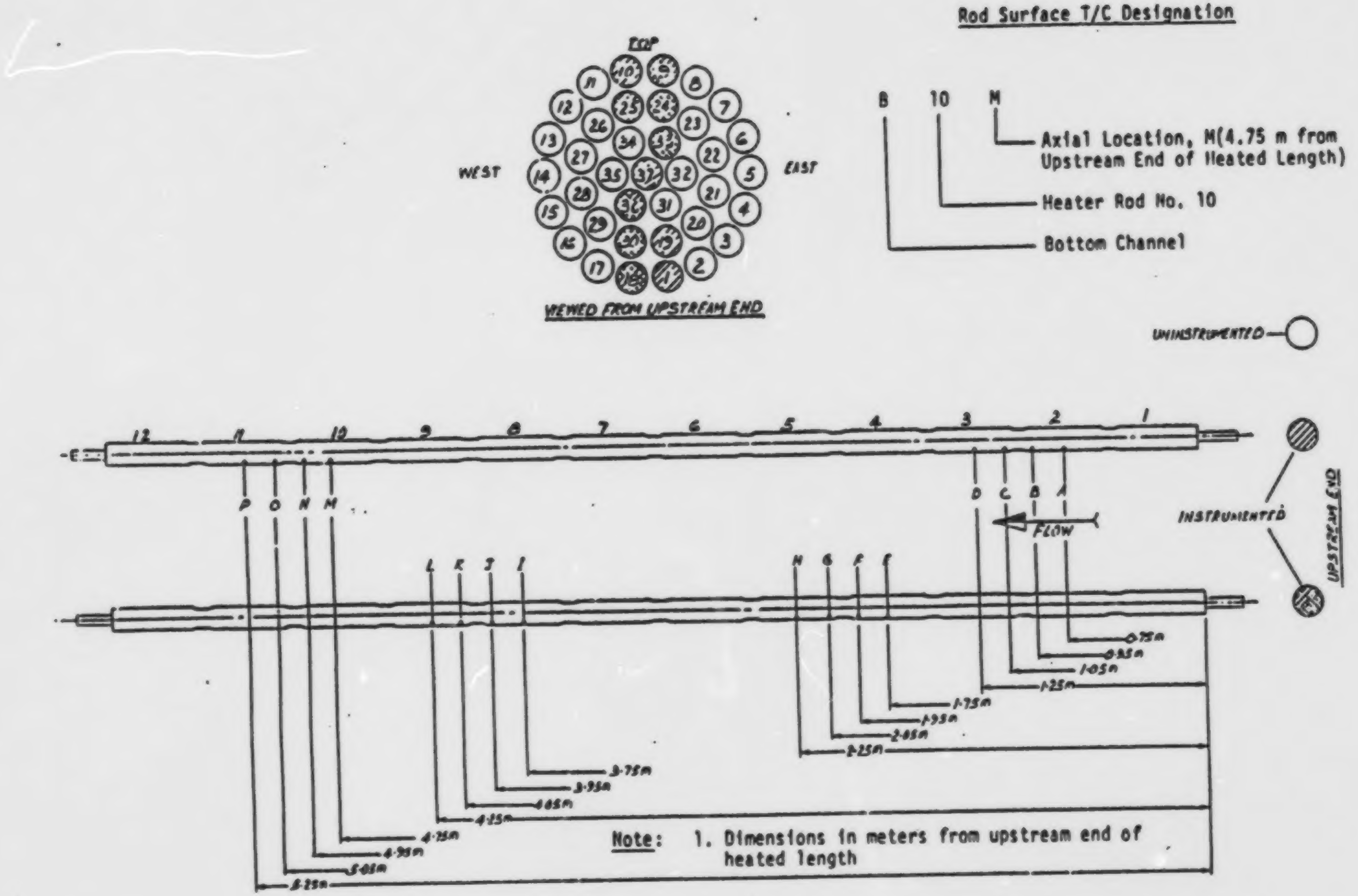

EHL
BHL
℄
3.0 m
3.0 m
5.25 m
3.75 m
2.25 m
0.75m
P
I
H
A
345 0 330 315 300 285 270 255 240 225 210 180 90
345 0 15 30 45 60 75 90 105 120 135 150 180 270 300 315 330
330 345 0 15 30 45 60 90 180 210 225 240 255 270 285 300 315
0 15 30 45 60 75 90 105 120 135 150 180 270

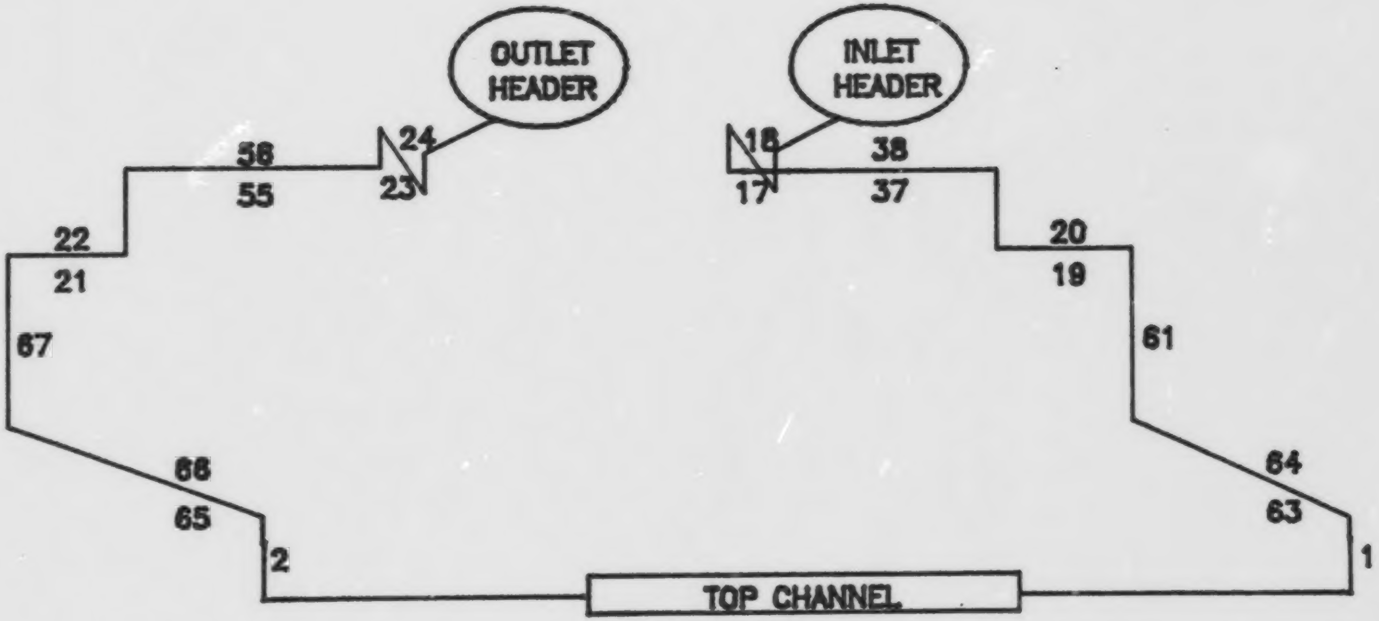
FIGURE 3: THERMOCOUPLES ARRANGEMENTS FOR PRESSURE TUBE



TOP
WEST
EAST
VIEWED FROM UPSTREAM END
Rod Surface T/C Designation
B 10 M
Axial Location, M(4.75 m from Upstream End of Heated Length)
Heater Rod No. 10
Bottom Channel
UNINSTRUMENTED
INSTRUMENTED
UPSTREAM END
FLOW
12 11 10 9 8 7 6 5 4 3 2 1
P O N M
D C B A
L K J I
H G F E
0.75m
0.95m
1.05m
1.25m
1.75m
1.95m
2.05m
2.25m
3.75m
3.95m
4.05m
4.25m
4.75m
4.95m
5.05m
5.25m

Note: 1. Dimensions in meters from upstream end of heated length

FIGURE 4: LOCATIONS OF THERMOCOUPLES FOR THE 37-ELEMENT FUEL STRING



OUTLET HEADER
INLET HEADER
56
55
24
23
18
17
38
37
22
21
20
19
67
61
66
65
64
63
2
1
TOP CHANNEL

FIGURE 5: SCHEMATIC DIAGRAM OF THE TOP CHANNEL FEEDERS

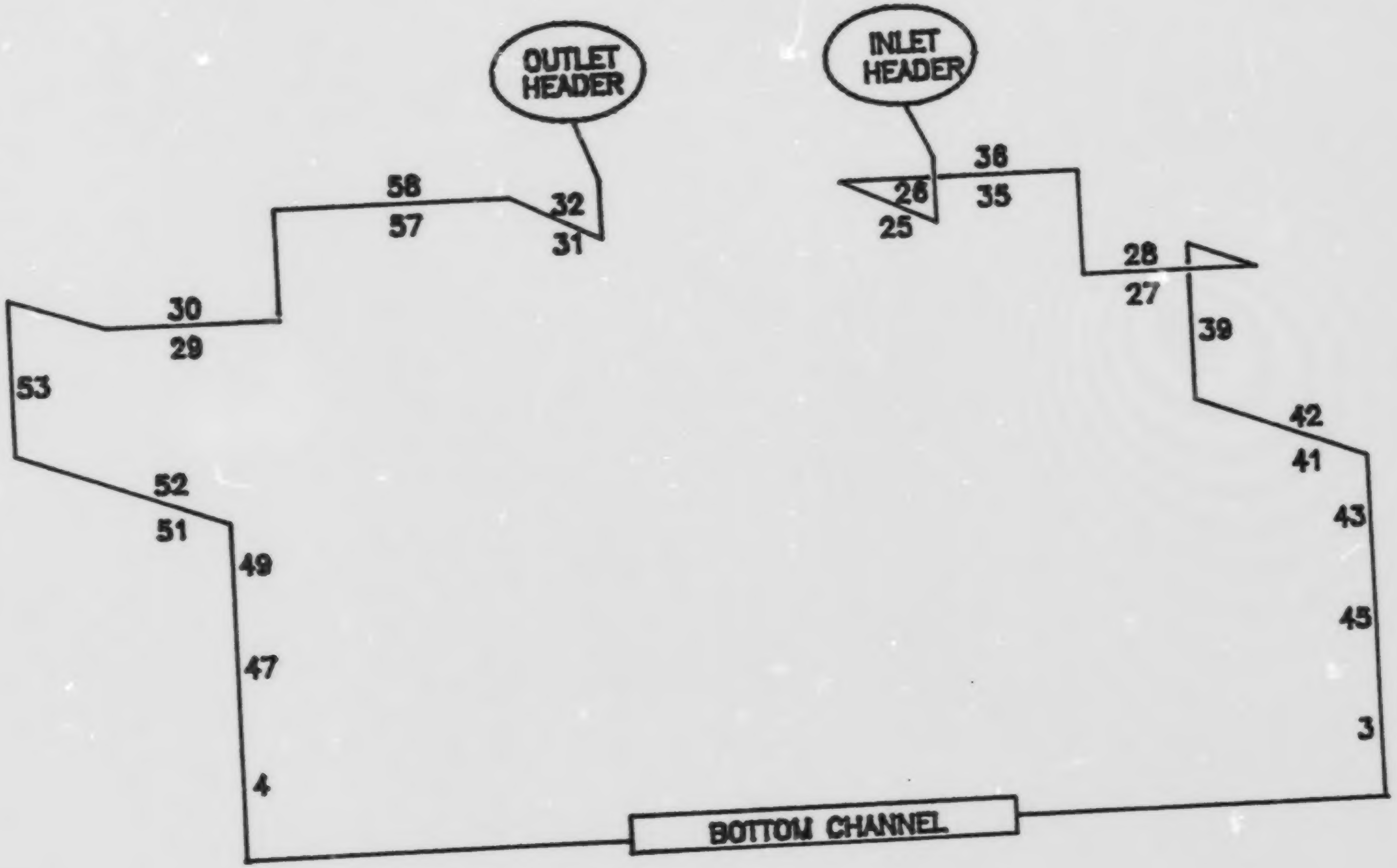

OUTLET HEADER
INLET HEADER
58
57
32
31
36
35
26
25
28
27
39
30
29
53
42
41
43
45
3
52
51
49
47
4
BOTTOM CHANNEL

FIGURE 6: SCHEMATIC DIAGRAM OF BOTTOM CHANNEL FEEDERS

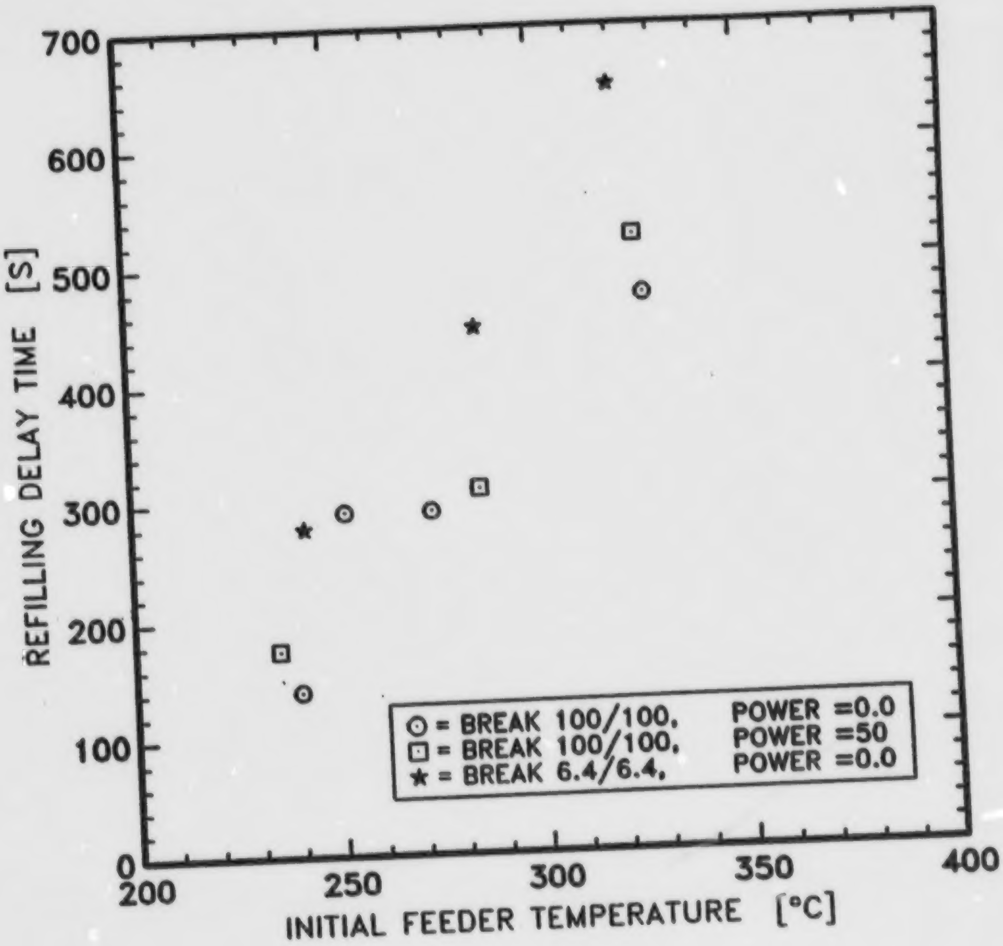


FIGURE 7: EFFECT OF INITIAL FEEDER TEMPERATURE, CHANNEL POWER, AND BREAK SIZE ON FEEDER REFILLING. REPORT SL-010

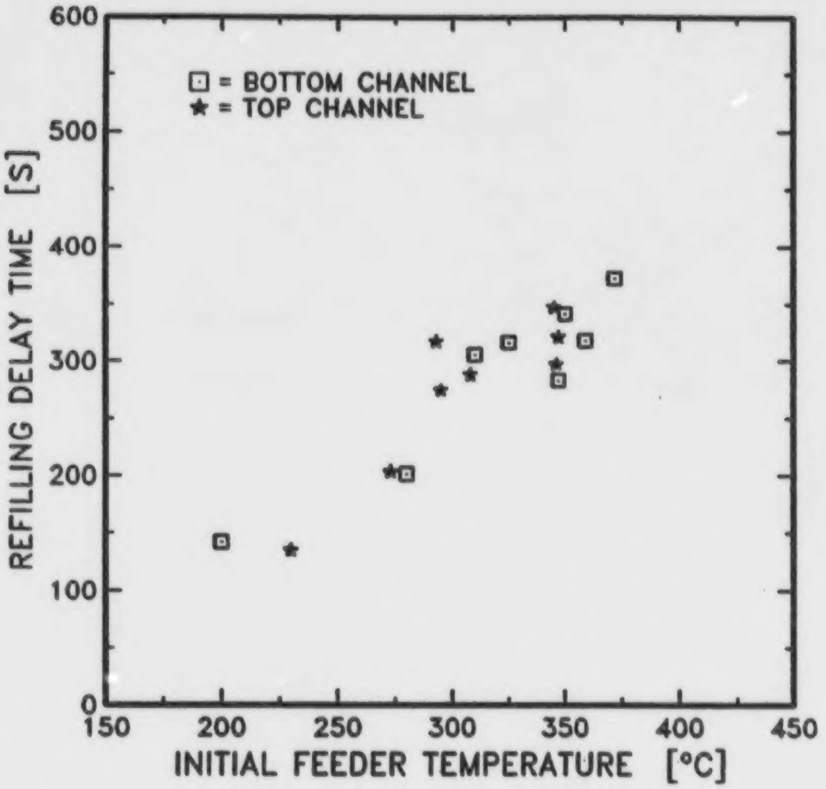


FIGURE 8: FEEDER REFILL TIMES FOR
BOTTOM AND TOP CHANNELS.
REPORTS CWAPD-480 & 481
100/100 BREAK

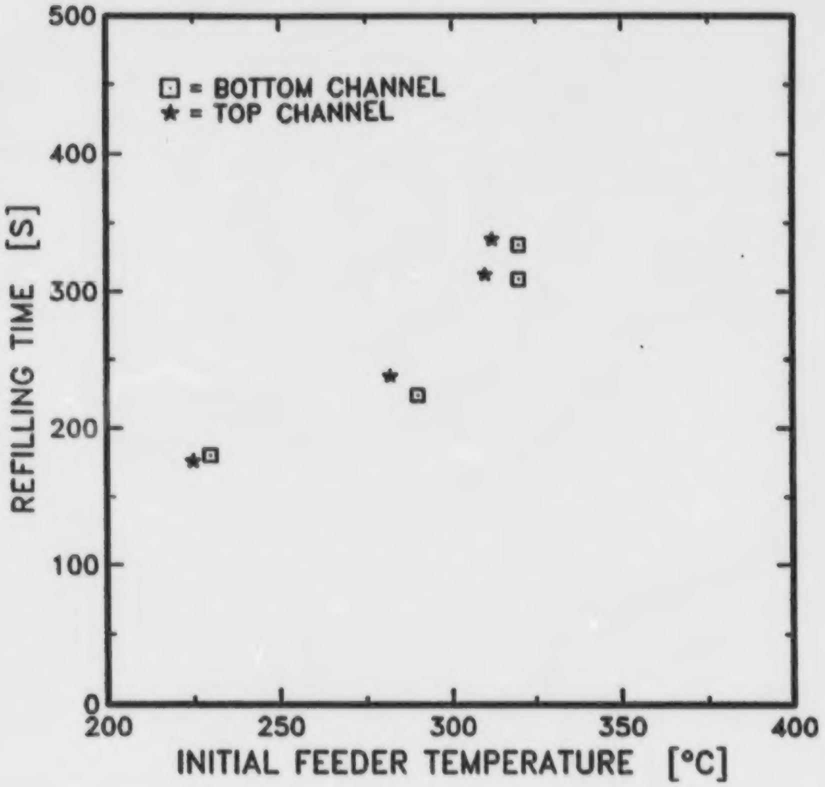


FIGURE 9: FEEDER REFILL TIMES FOR TOP AND BOTTOM CHANNELS.
REPORT SL-010
100/100 BREAK POWER=0.0

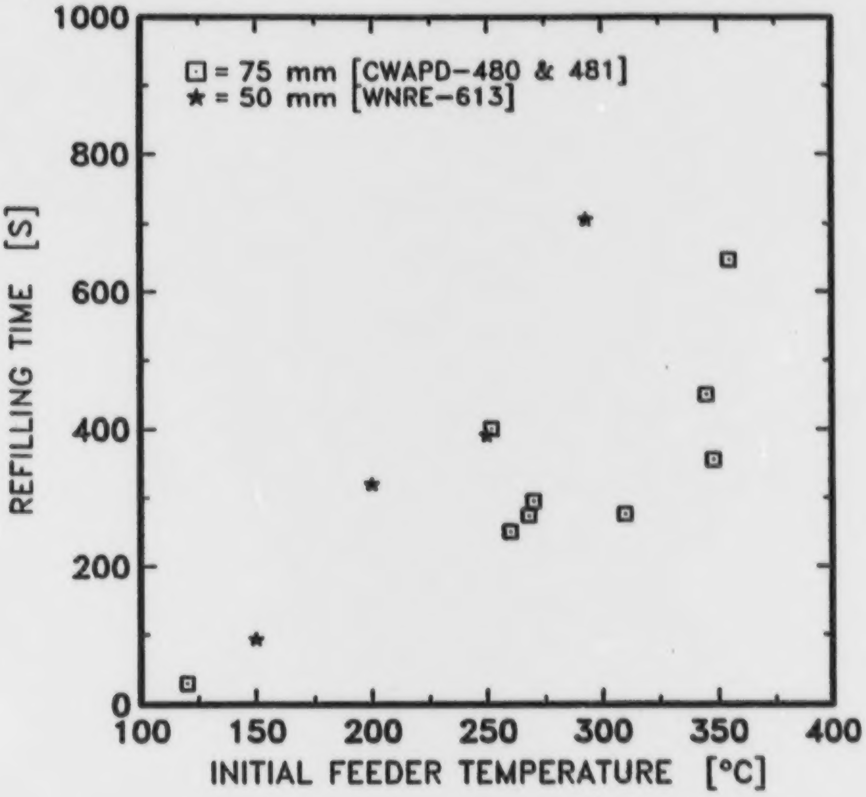


FIGURE 10: EFFECT OF CHANGING THE DIAMETER OF THE FEEDER CONNECTIONS TO THE HEADERS ON FEEDER REFILLING TIME.

SINGLE (BOTTOM) CHANNEL TESTS
100/100 BREAK AND POWER=0.0

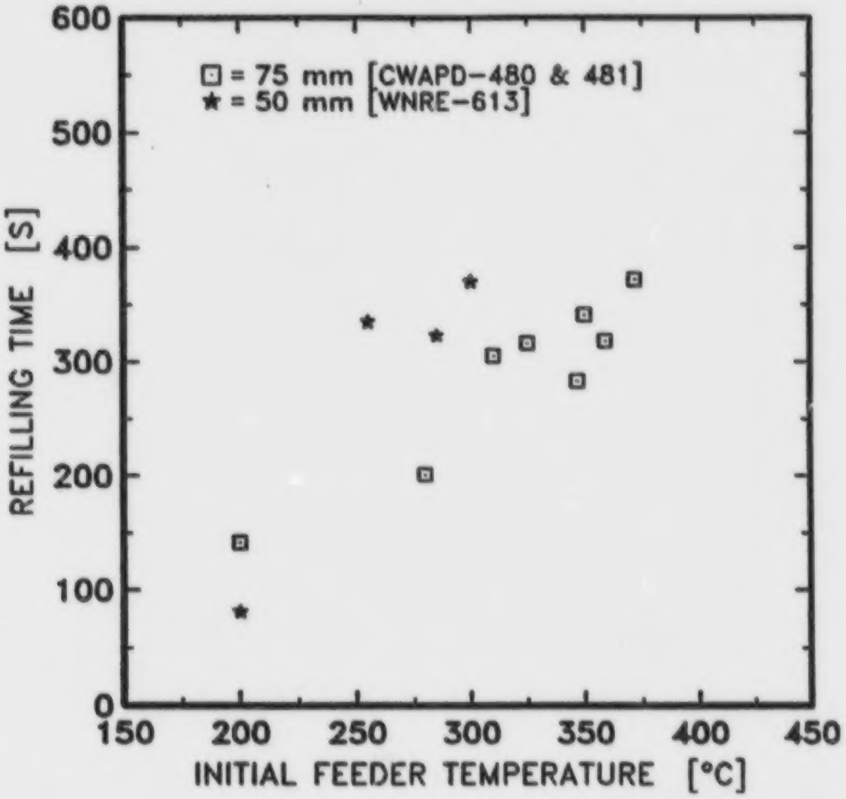


FIGURE 11: EFFECT OF CHANGING THE DIAMETER OF THE FEEDER CONNECTIONS TO THE HEADERS ON FEEDER REFILLING TIME.

BOTTOM CHANNEL OF DOUBLE CHANNEL TESTS
100/100 BREAK AND POWER=0.0

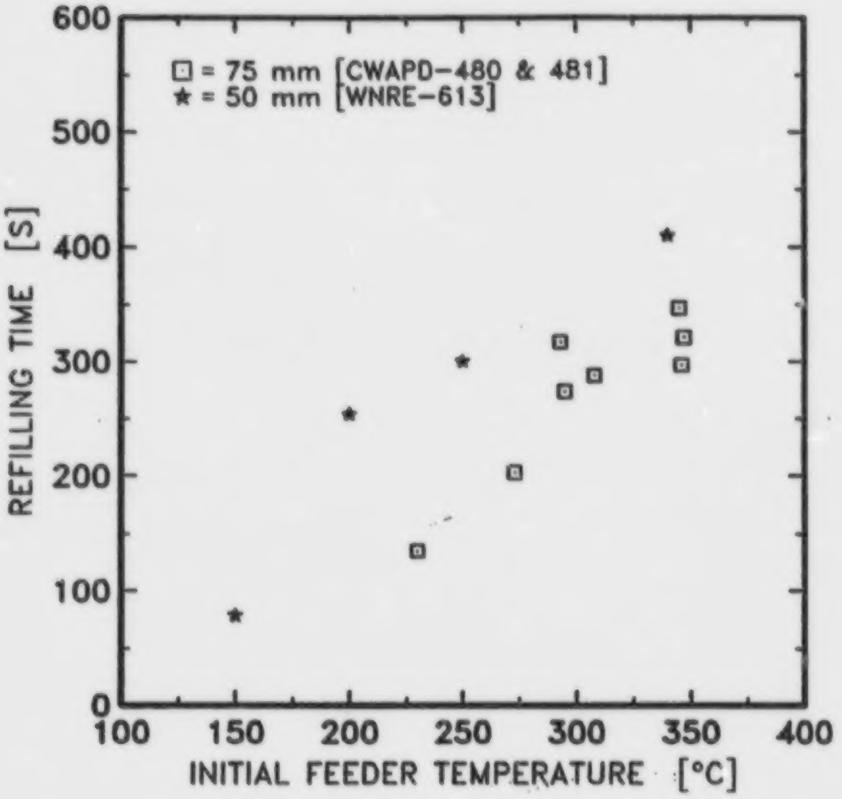


FIGURE 12: EFFECT OF CHANGING THE DIAMETER OF THE FEEDER CONNECTIONS TO THE HEADERS ON FEEDER REFILLING TIME.

TOP CHANNEL OF DOUBLE CHANNEL TESTS
100/100 BREAK AND POWER=0.0

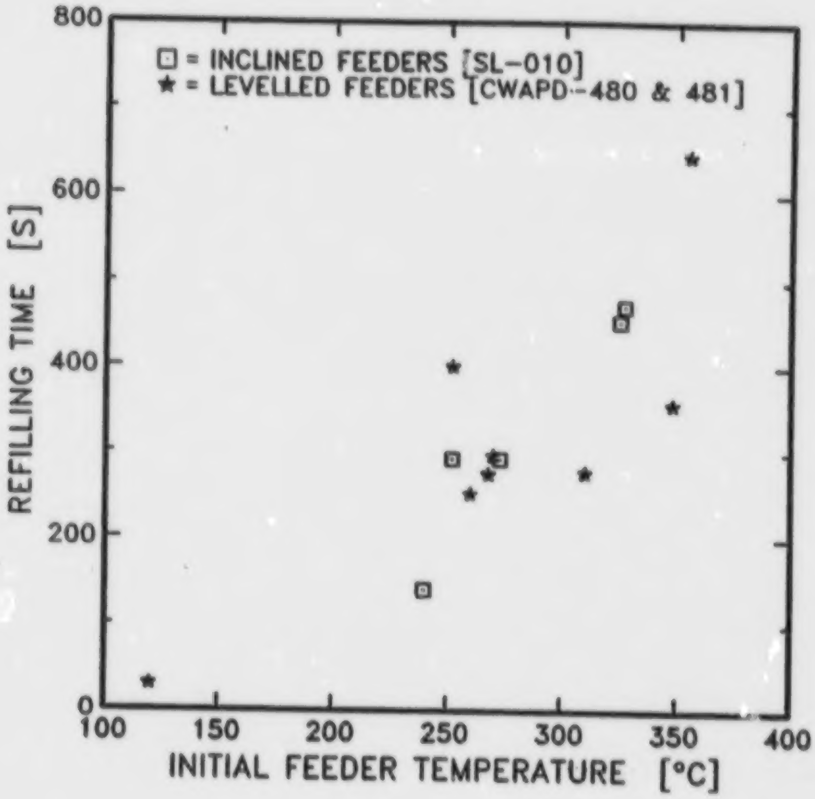


FIGURE 13: EFFECT OF FEEDER INCLINATION
ON FEEDER REFILLING TIME.
SINGLE (BOTTOM) CHANNEL TESTS
100/100 BREAK, POWER=0.0

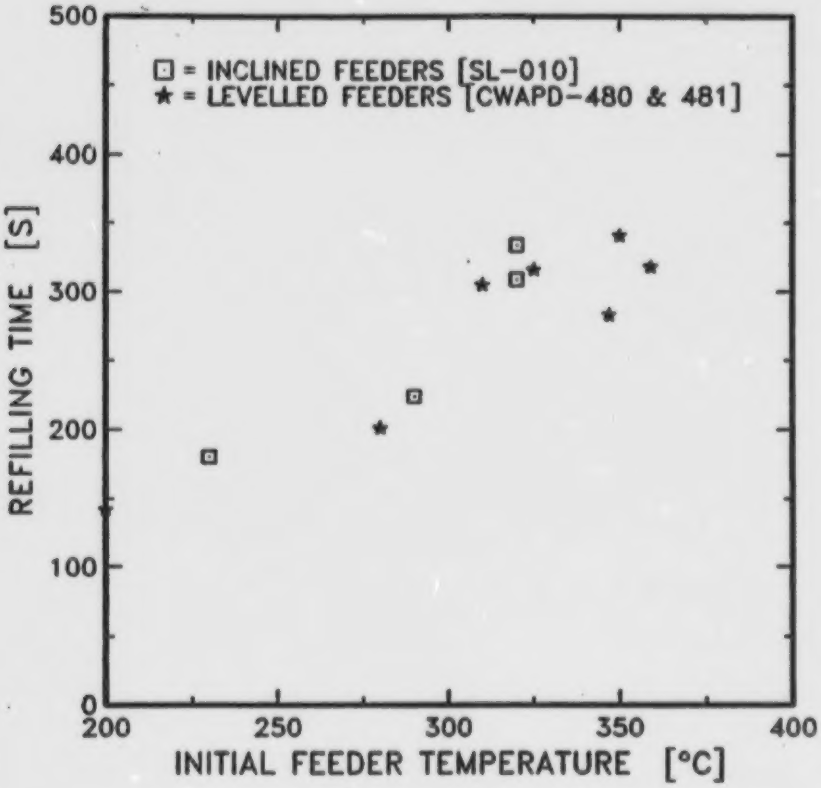


FIGURE 14: EFFECT OF FEEDER INCLINATION ON FEEDER REFILLING TIME.
DOUBLE CHANNEL TESTS – BOTTOM CHANNEL
100/100 BREAK, POWER=0.0

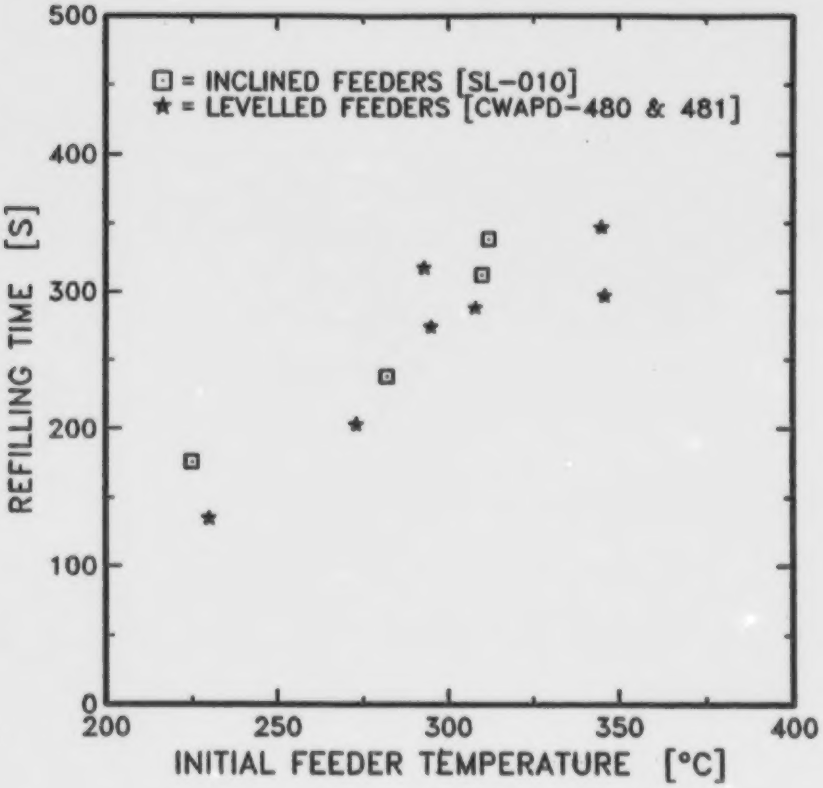


FIGURE 15: EFFECT OF FEEDER INCLINATION
ON FEEDER REFILLING TIME.
DOUBLE CHANNEL TESTS – TOP CHANNEL
100/100 BREAK, POWER=0.0

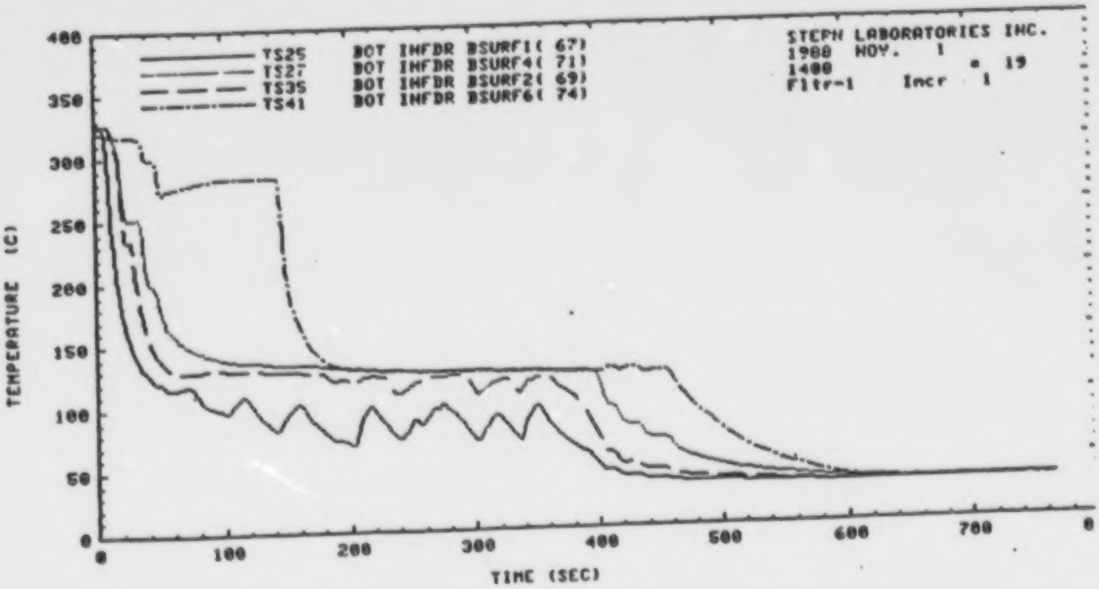


FIGURE 16: FEEDER SURFACE TEMPERATURE CURVES

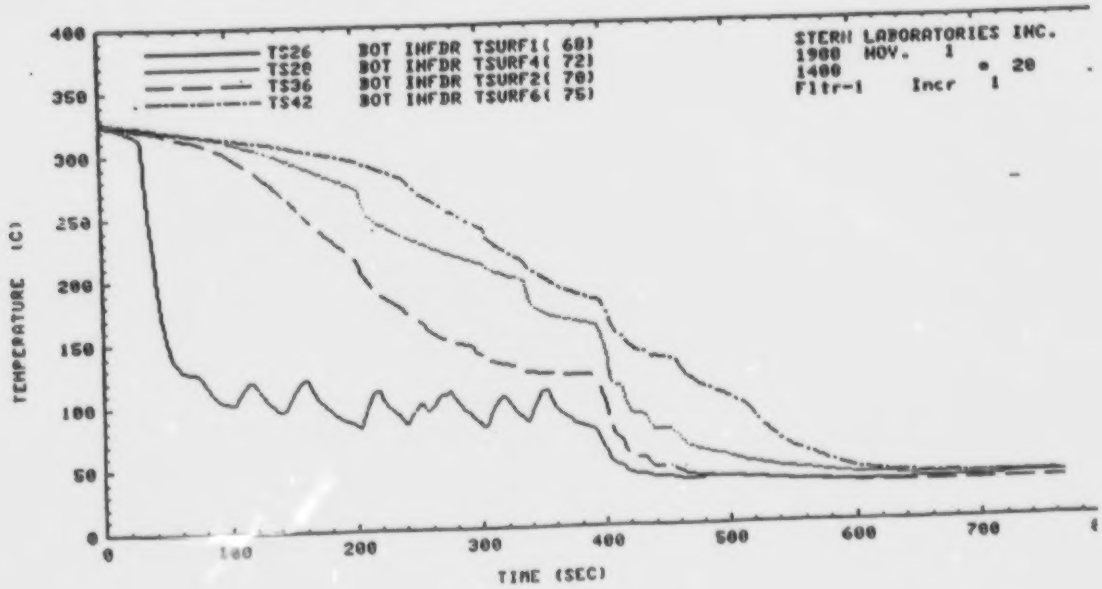


FIGURE 17: FEEDER SURFACE TEMPERATURE CURVES

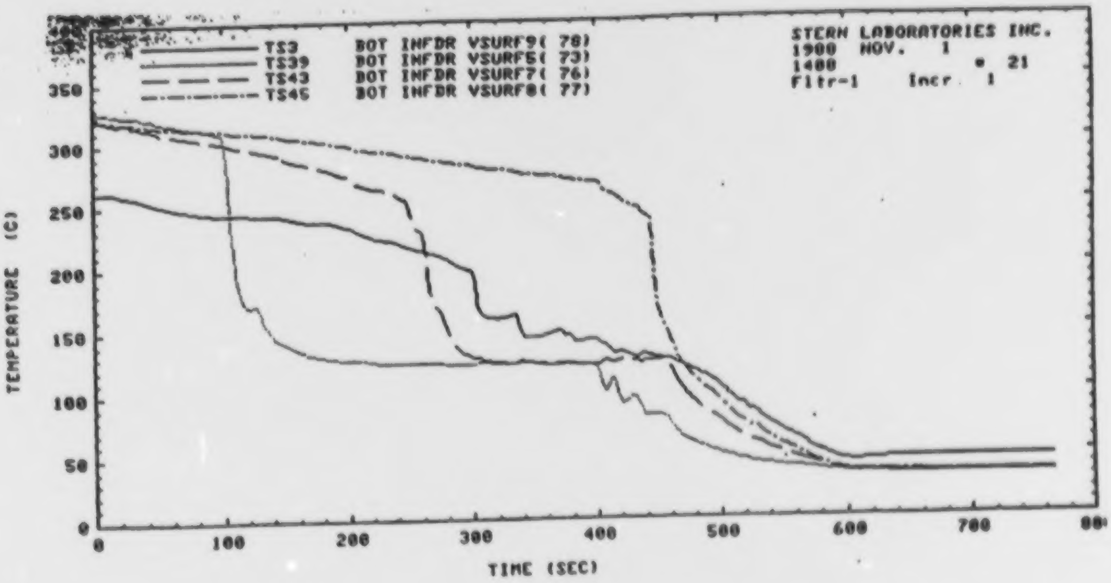


FIGURE 18: FEEDER SURFACE TEMPERATURE CURVES

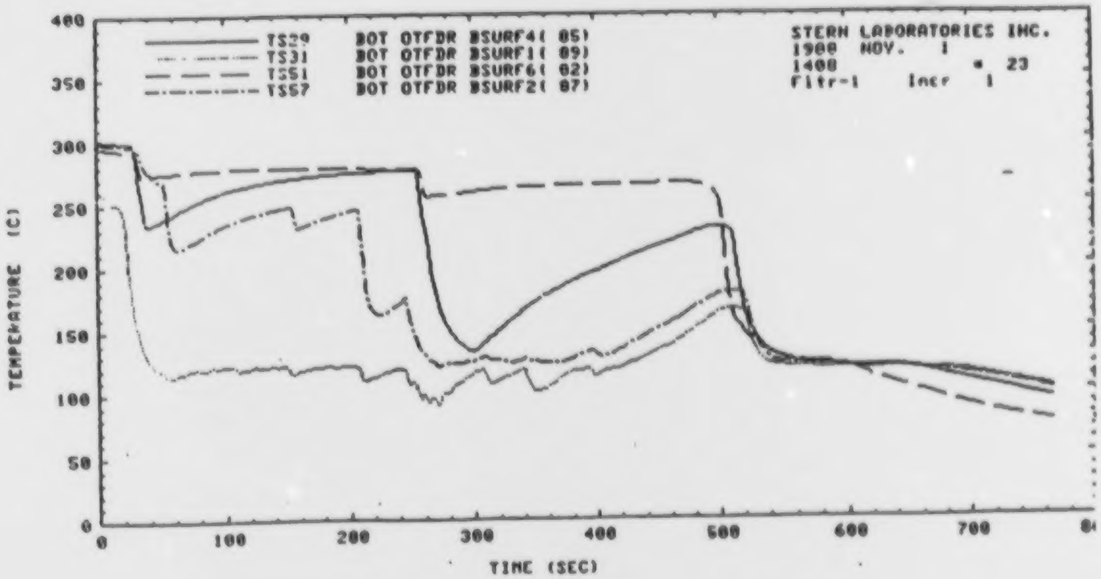


FIGURE 19: FEEDER SURFACE TEMPERATURE CURVES

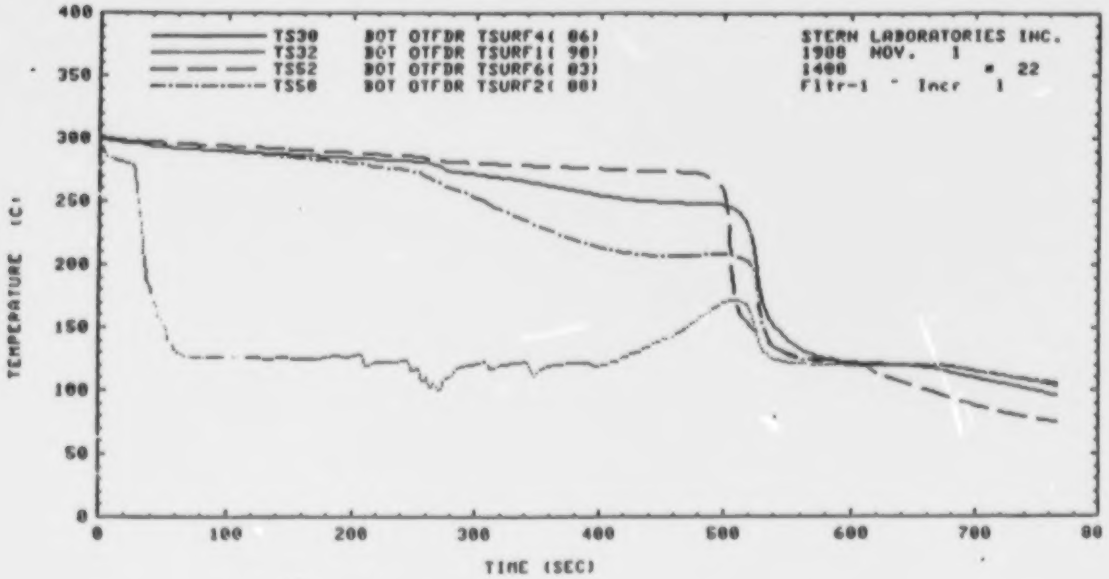


FIGURE 20: FEEDER SURFACE TEMPERATURE CURVES

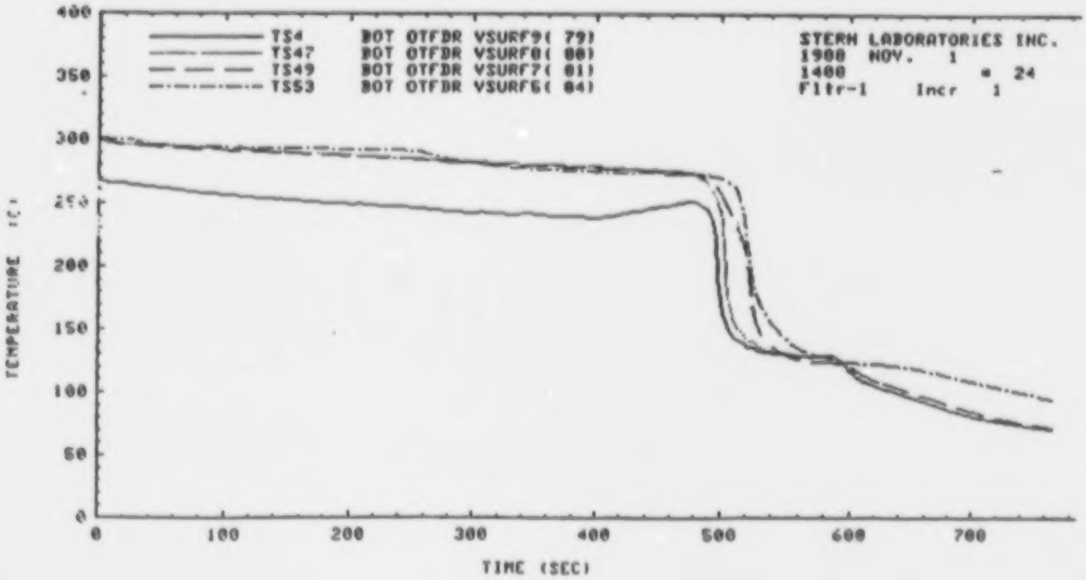


FIGURE 21: FEEDER SURFACE TEMPERATURE CURVES

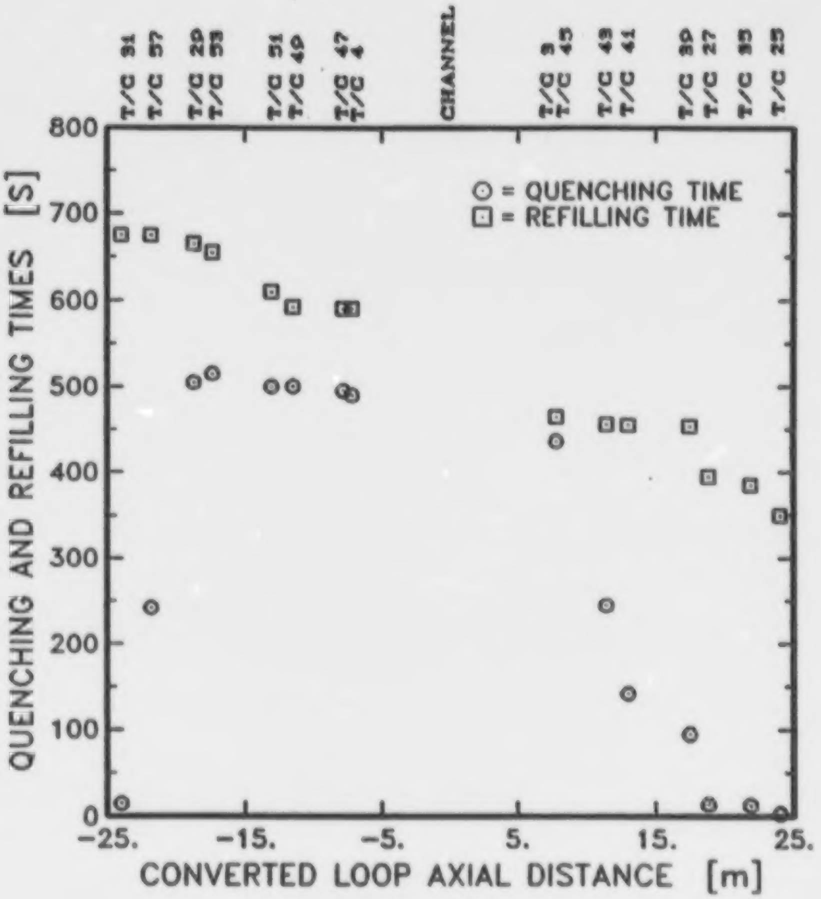


FIGURE 22: PROPAGATION OF QUENCHING & REFILLING FRONTS IN THE FEEDERS.

TEST 1408
SINGLE (BOTTOM) CHANNEL
100/100 BREAK
CHANNEL POWER = 0.0

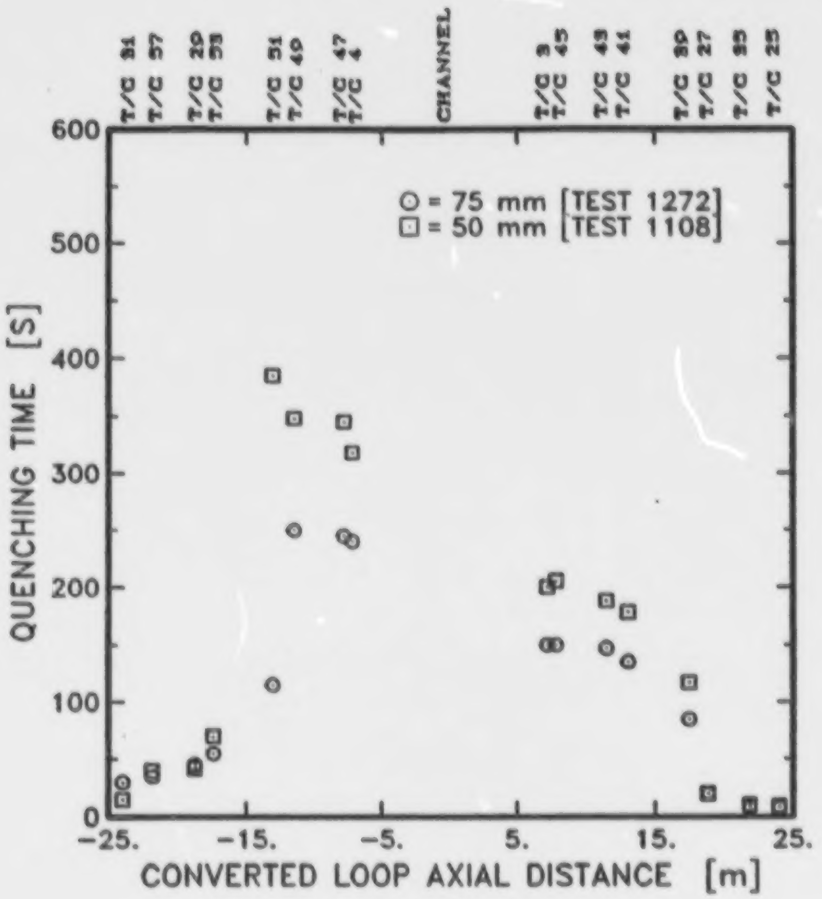


FIGURE 23: EFFECT OF CHANGING THE DIAMETER OF THE FEEDER CONNECTIONS TO THE HEADERS ON QUENCH FRONT PROPAGATION IN THE FEEDERS.

BOTTOM CHANNEL DATA
6.4/6.4 BREAK

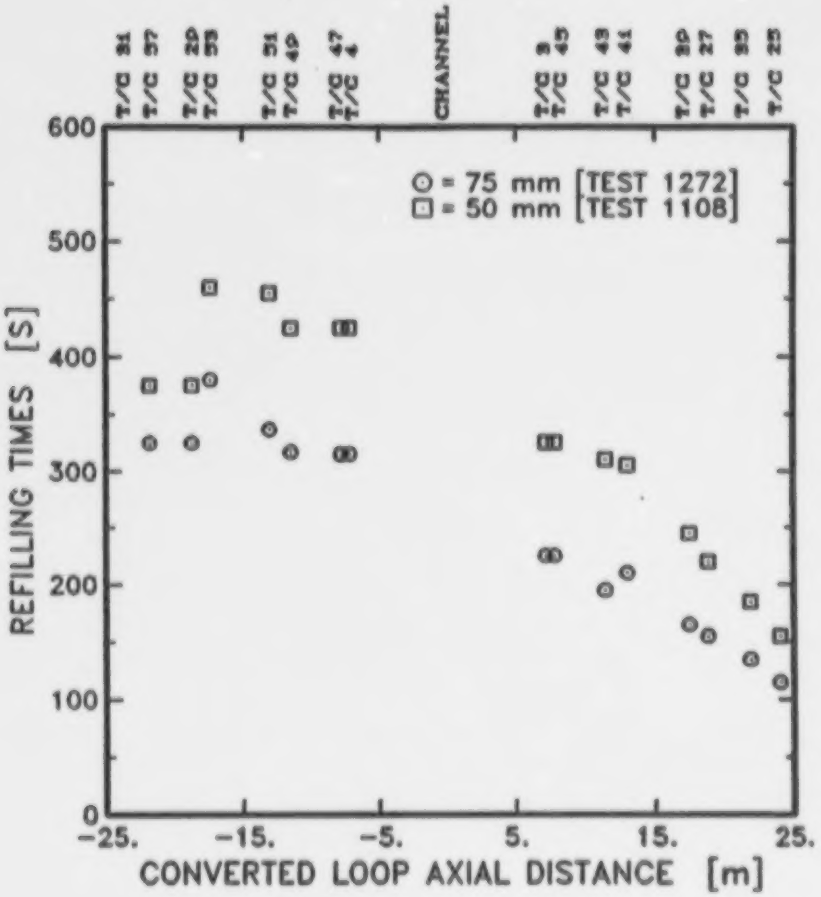


FIGURE 24: EFFECT OF CHANGING THE DIAMETER OF THE FEEDER CONNECTIONS TO THE HEADERS ON REFILL FRONT PROPAGATION IN THE FEEDERS.

BOTTOM CHANNEL DATA
6.4/6.4 BREAK

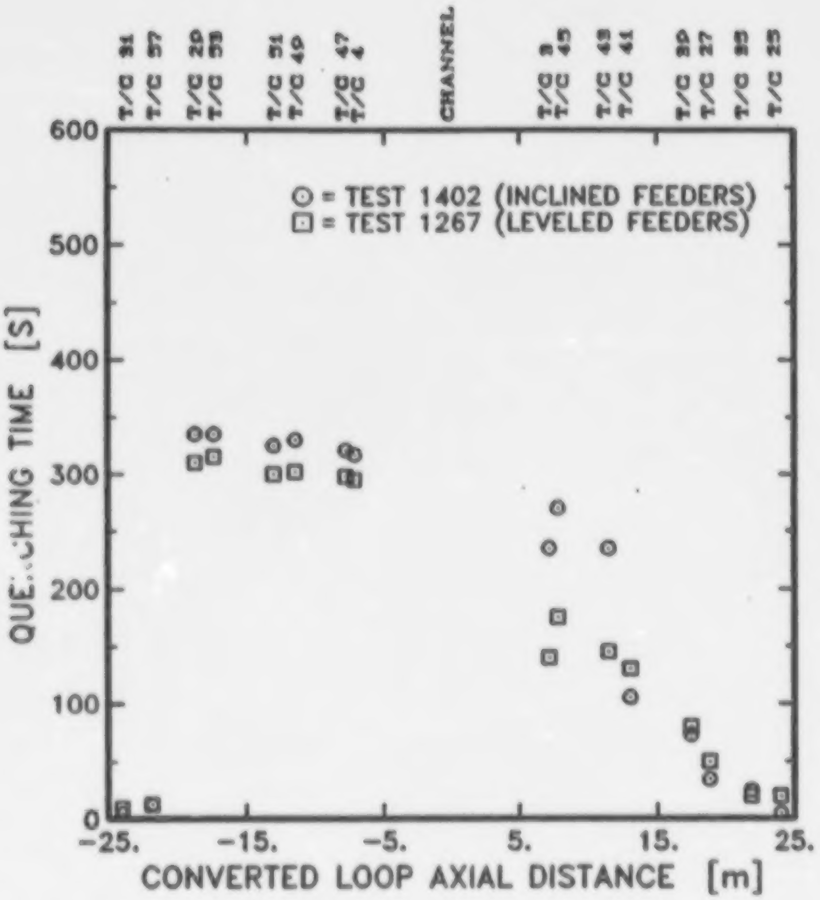


FIGURE 25: EFFECT OF FEEDER INCLINATION
ON QUENCH FRONT PROPAGATION
IN THE FEEDERS.

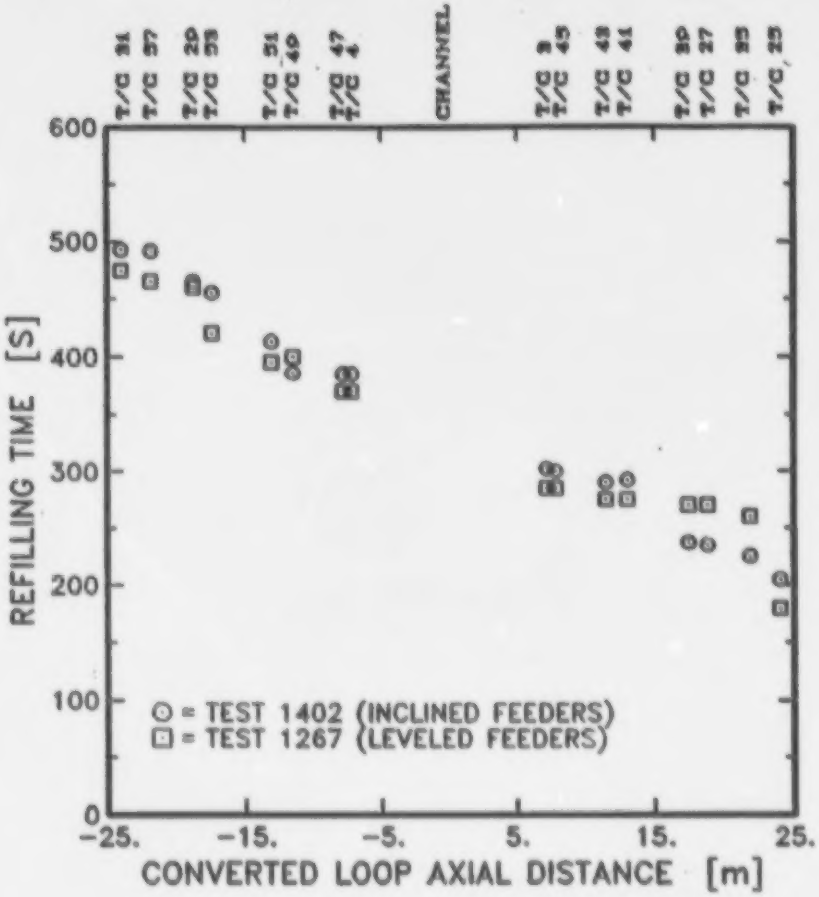


FIGURE 26: EFFECT OF FEEDER INCLINATION ON THE REFILLING FRONT PROPAGATION IN THE FEEDERS.

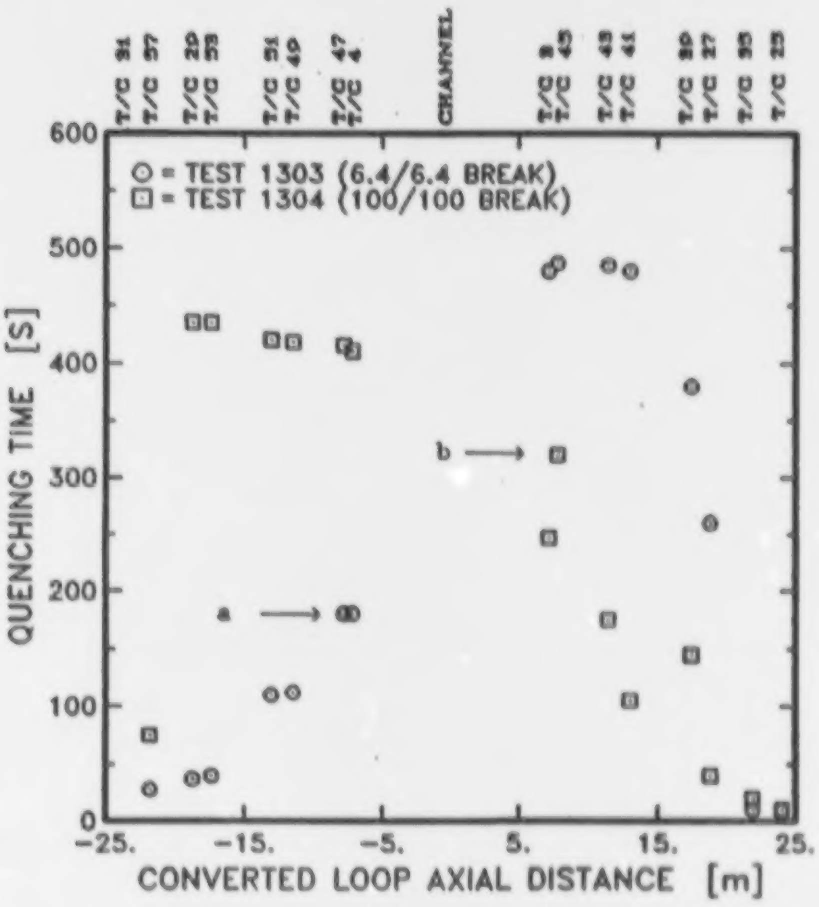


FIGURE 27: EFFECT OF BREAK SIZE
ON QUENCH FRONT PROPAGATION
IN FEEDERS.

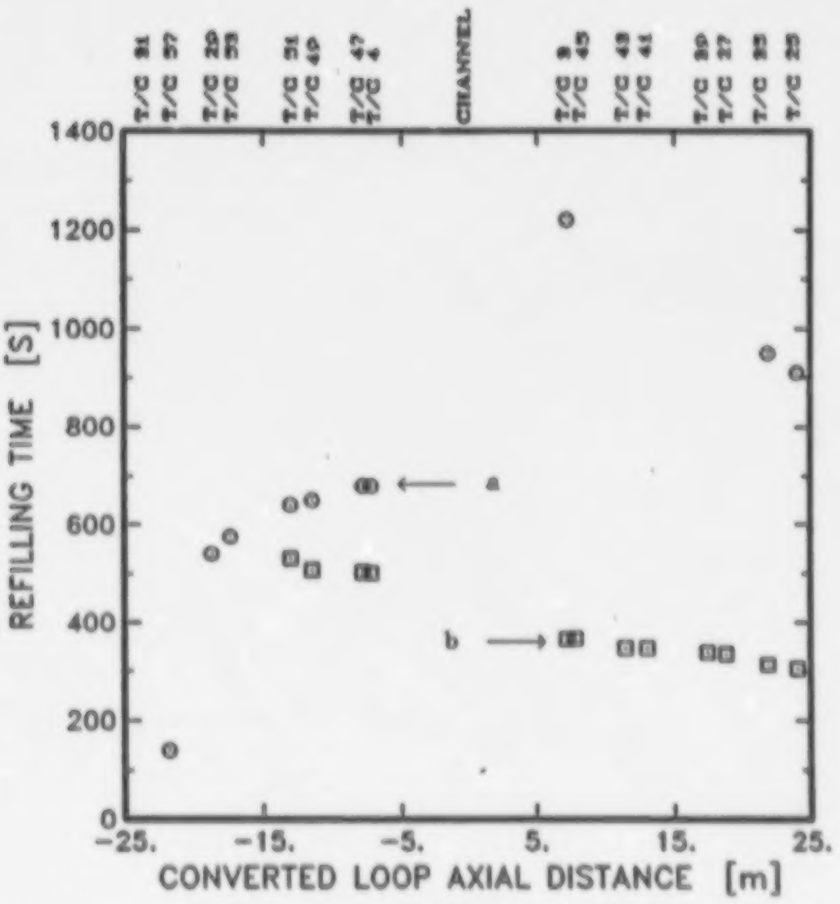


FIGURE 28: EFFECT OF BREAK SIZE
ON REFILL FRONT PROPAGATION
IN THE FEEDERS.

○ = TEST 1303 (4.6/4.6 BREAK)
☐ = TEST 1304 (100/100 BREAK)

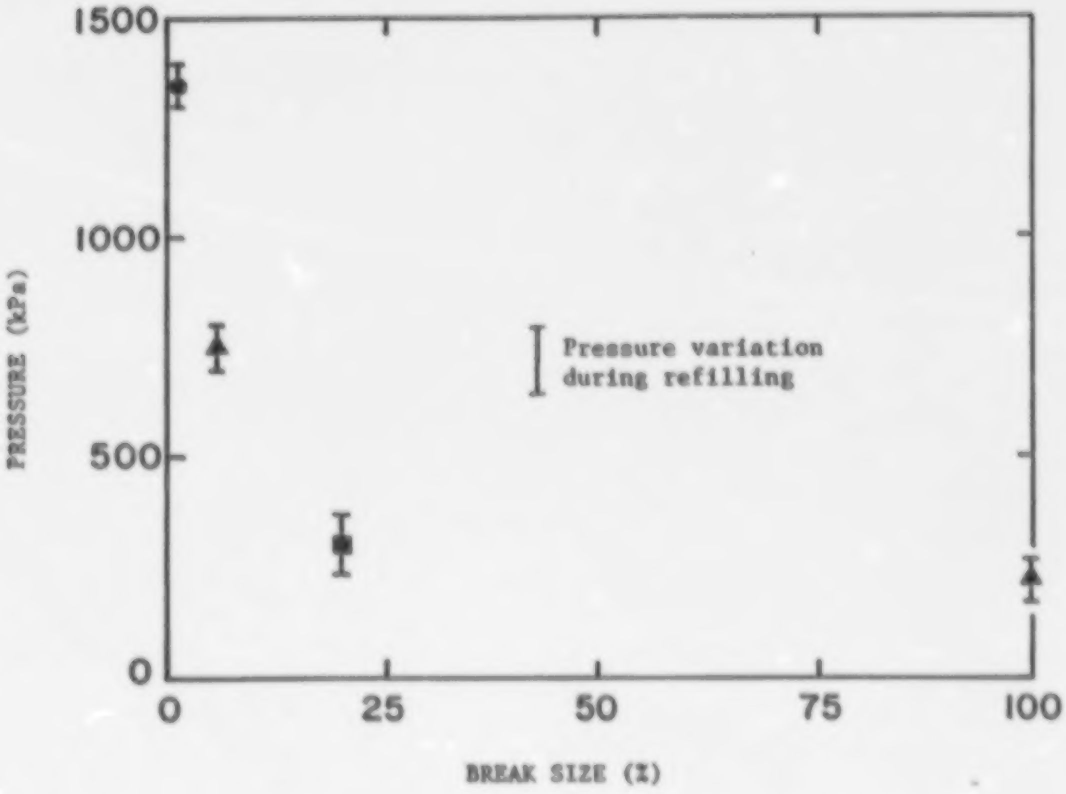


FIGURE 29: FEEDER PRESSURE DURING REFILLING
(SINGLE - CHANNEL TESTS)

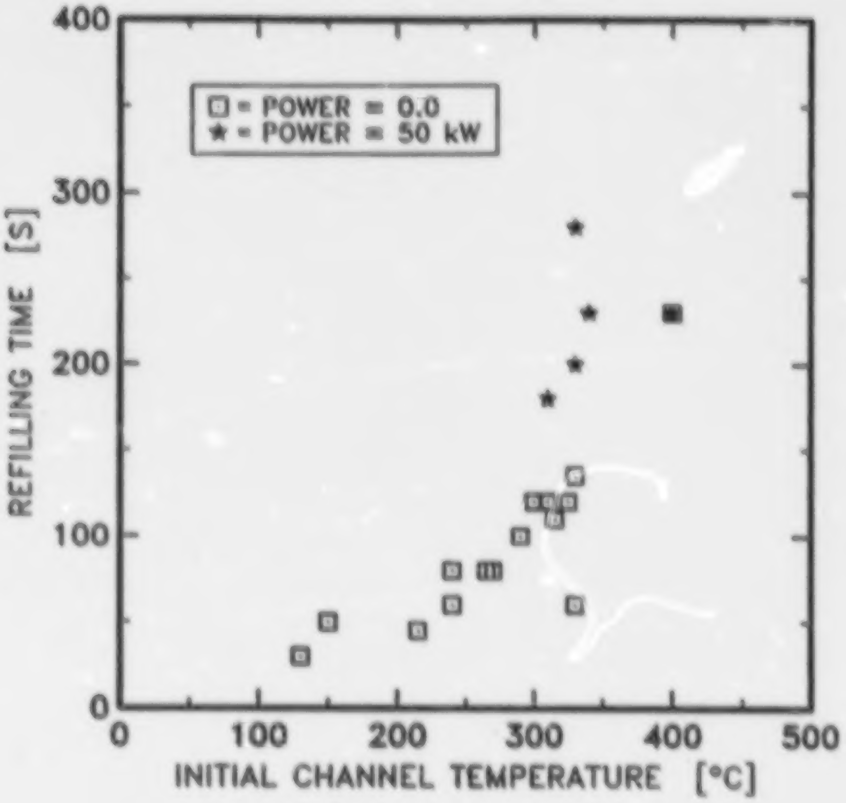


FIGURE 30: EFFECT OF CHANNEL POWER
ON CHANNEL REFILLING.

100%/100% BREAK
BOTTOM CHANNEL

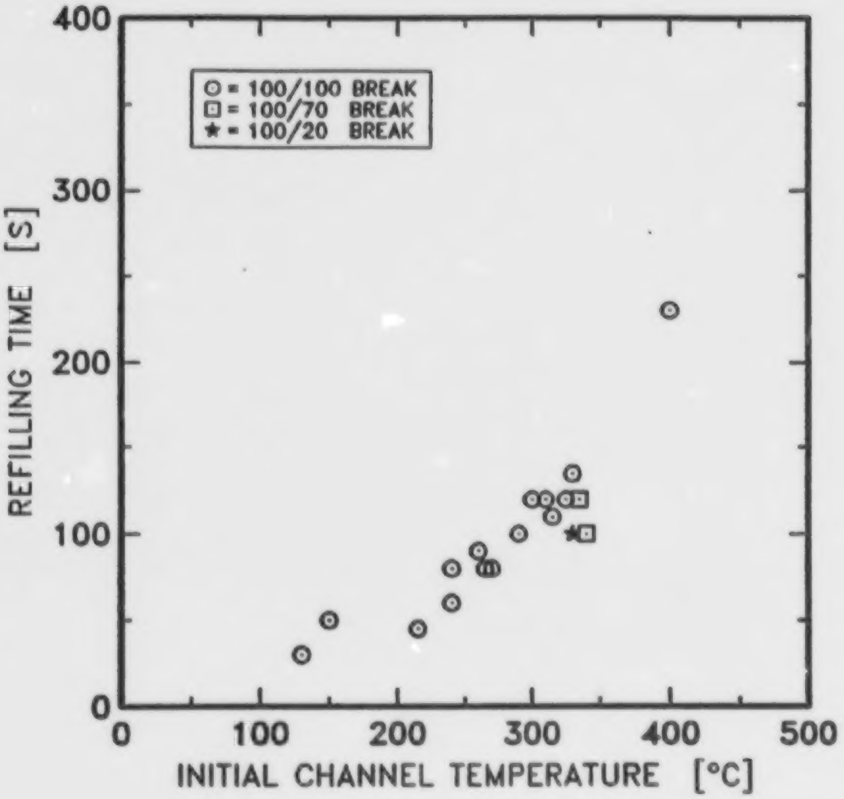


FIGURE 31: EFFECT OF ASYMMETRY IN BREAK SIZE ON CHANNEL REFILLING.

POWER=0.0
BOTTOM CHANNEL

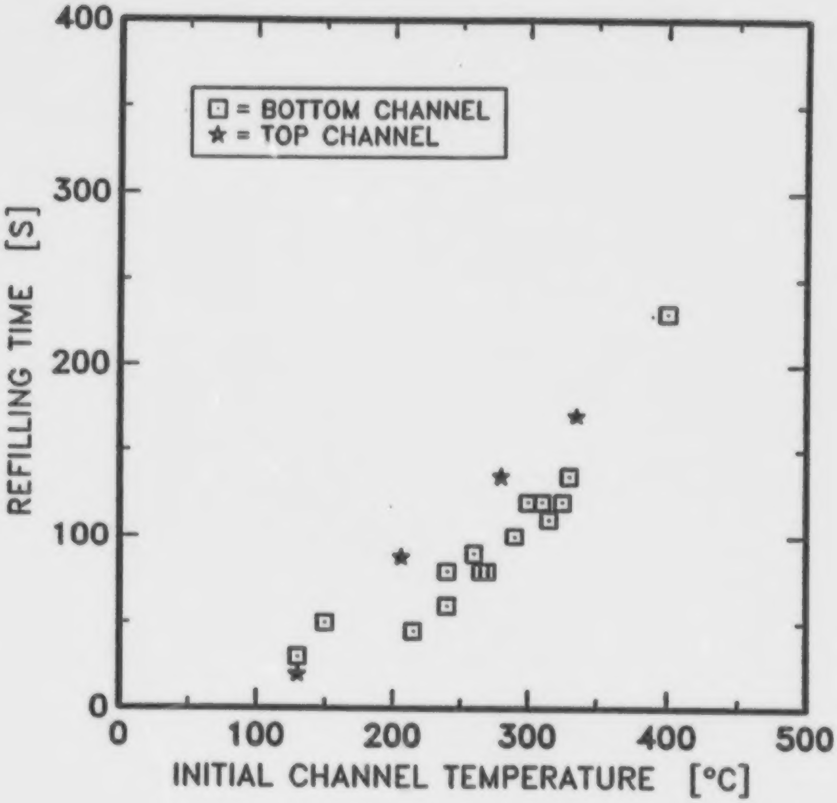


FIGURE 32: TOP AND BOTTOM CHANNEL REFILLING.

100/100 BREAK
POWER = 0.0

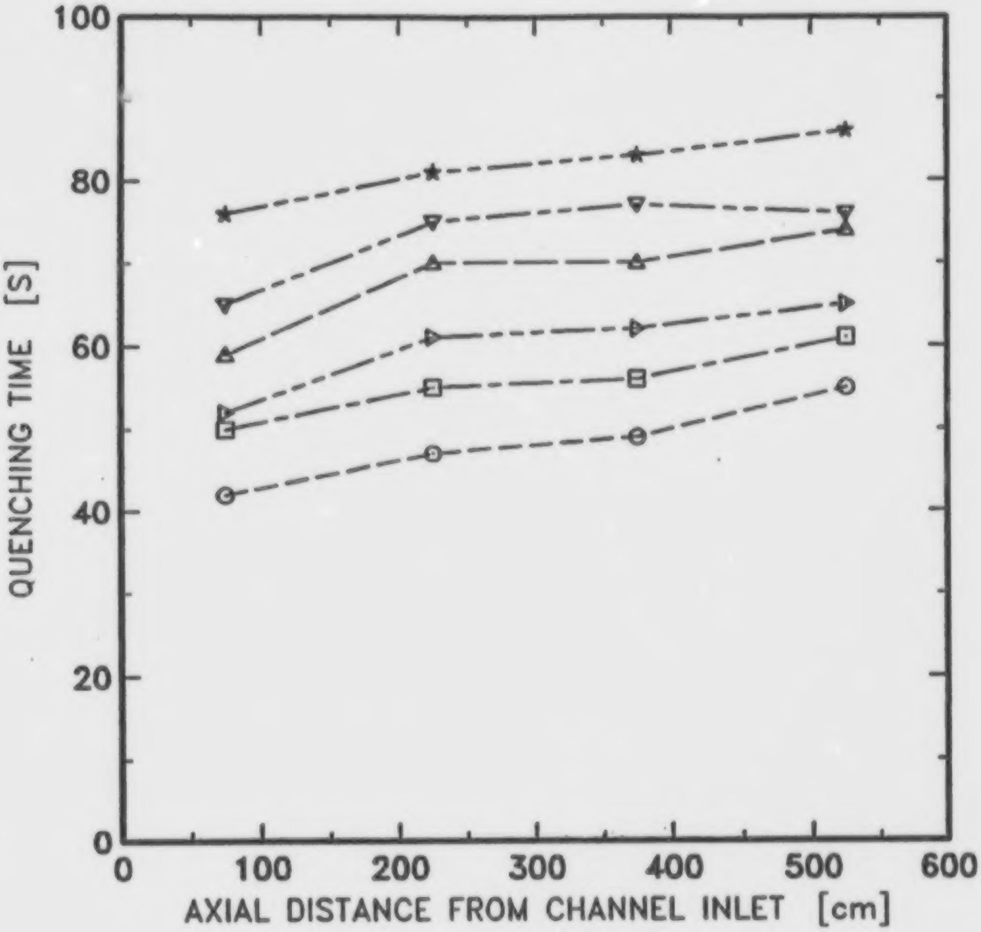


FIGURE 33: PRESSURE TUBE QUENCHING TIMES FOR SINGLE CHANNEL GAS INJECTION TESTS (REPORT CWAPD-460)

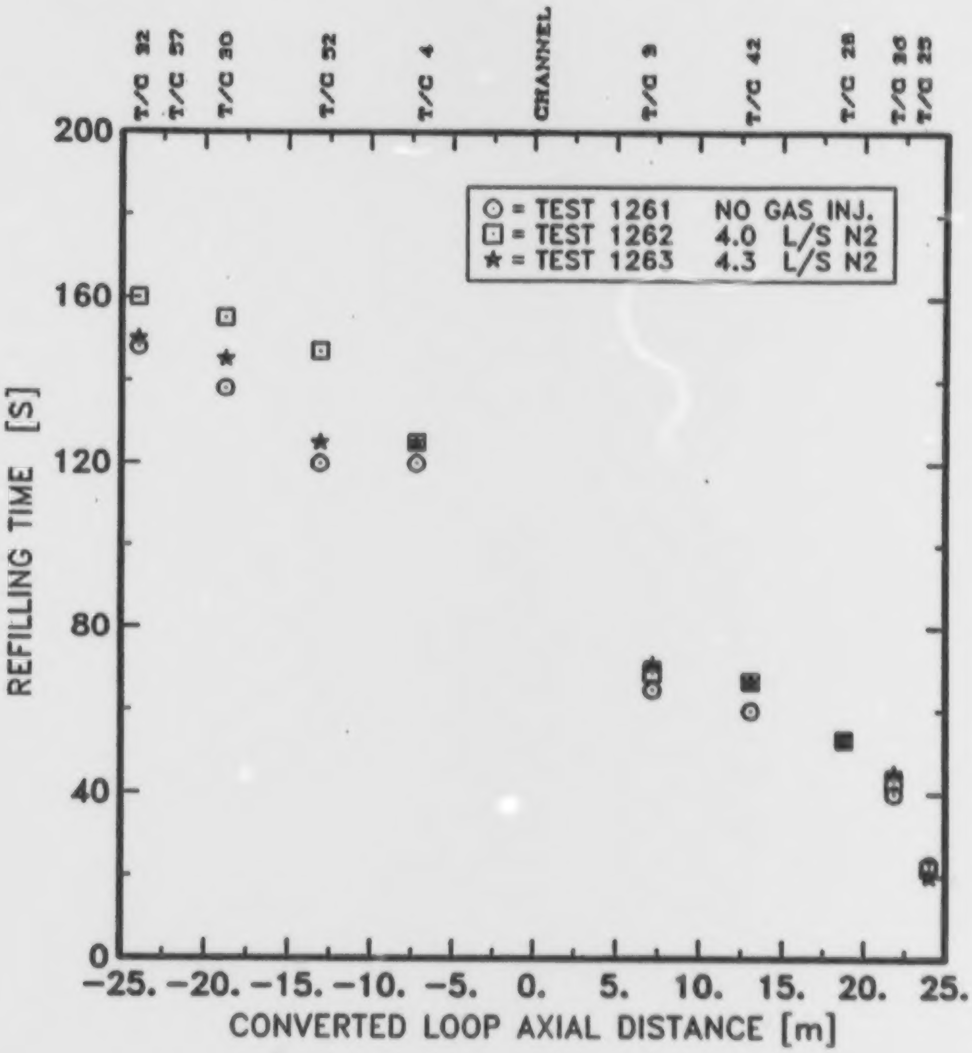


FIGURE 34: EFFECT OF GAS INJECTION ON FEEDER REFILLING TIMES OF SINGLE BREAK TESTS (REPORT CWAPD-460)

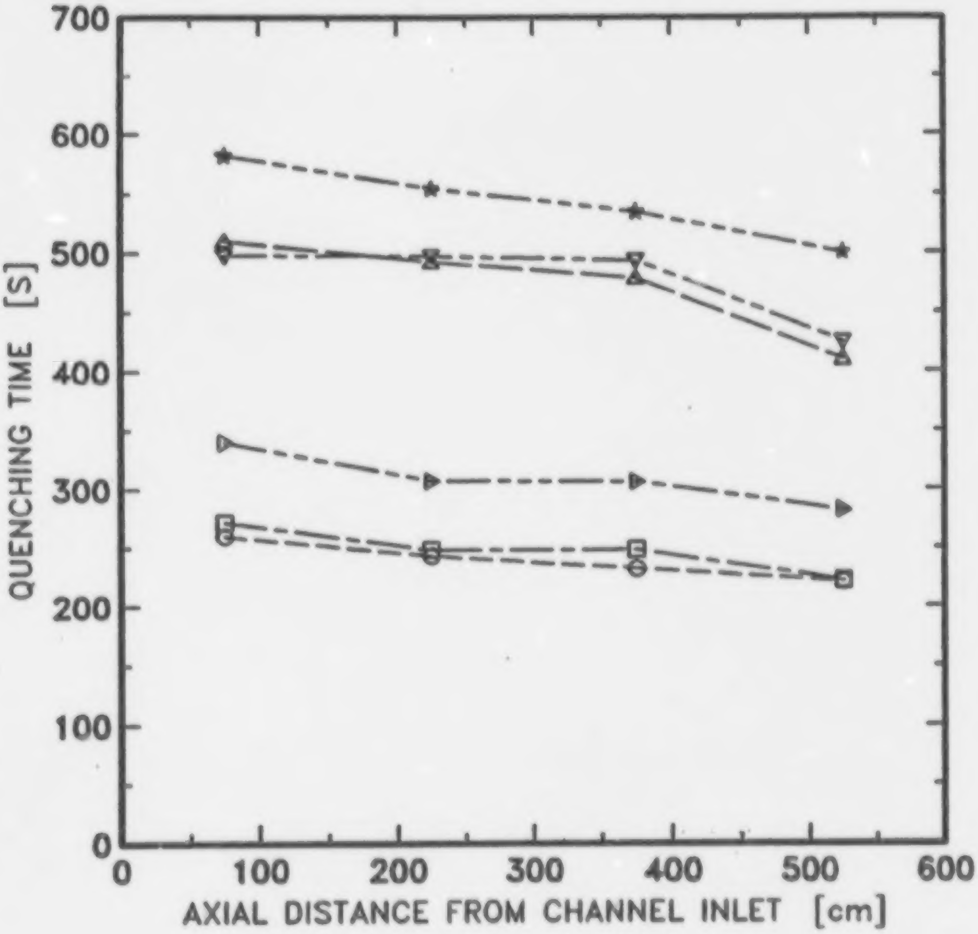


FIGURE 35: PRESSURE TUBE QUENCHING TIMES FOR DOUBLE BREAK GAS INJECTION TESTS (REPORT CWAPD-460)

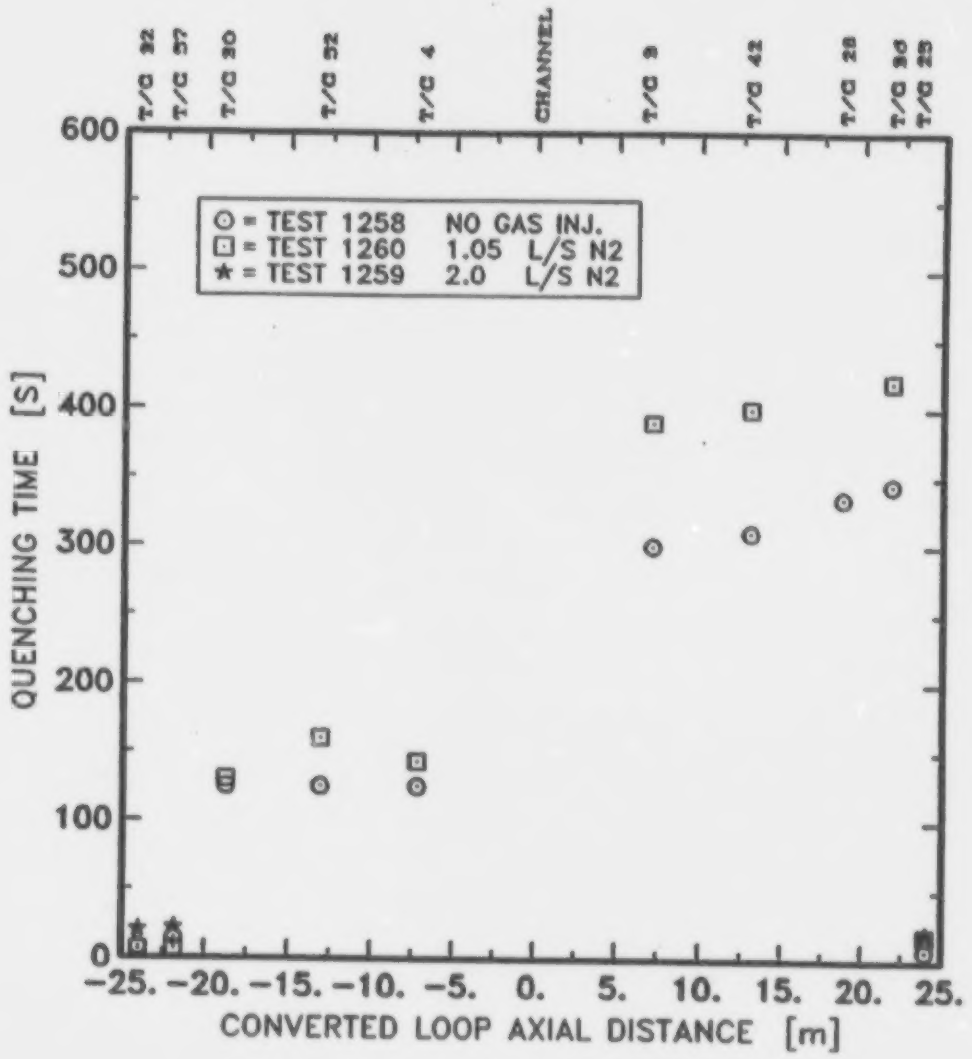


FIGURE 36: EFFECT OF GAS INJECTION ON FEEDER QUENCHING TIMES OF DOUBLE BREAK TESTS (REPORT CWAPD-460)

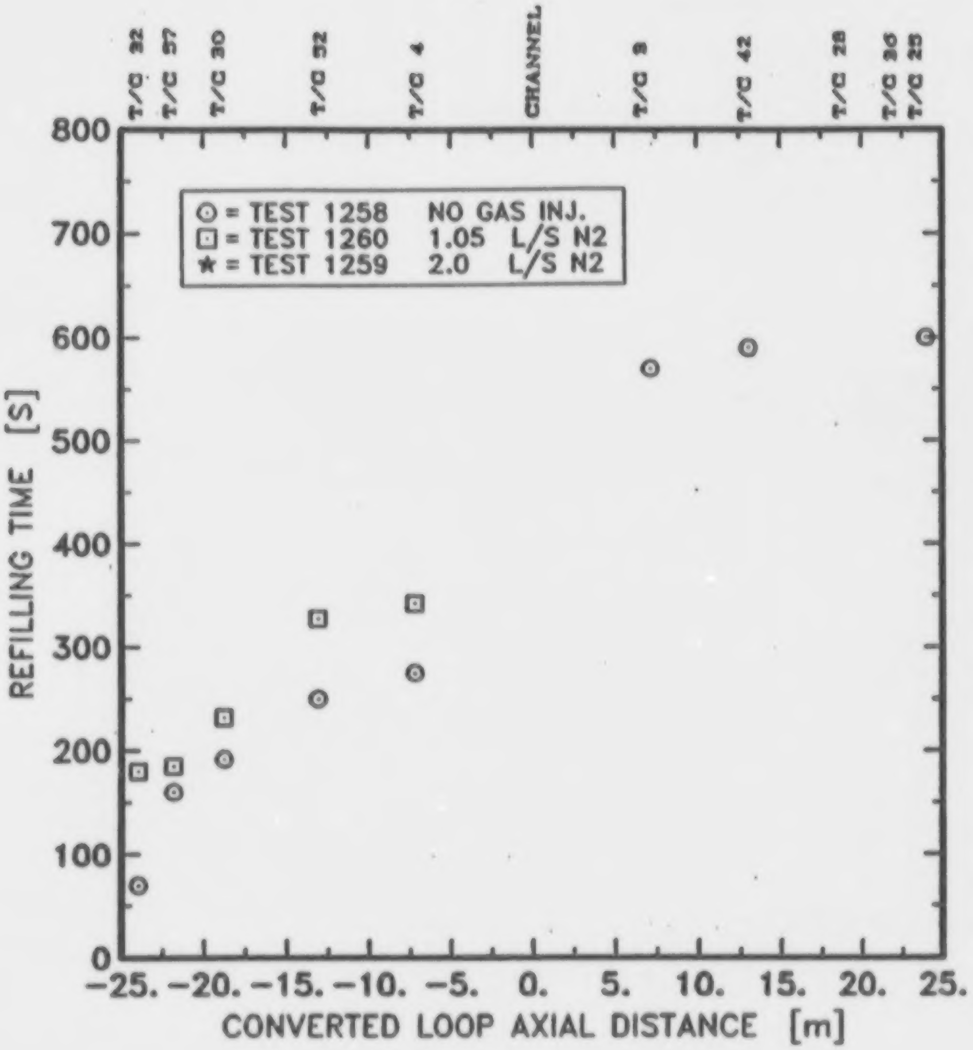


FIGURE 37: EFFECT OF GAS INJECTION ON FEEDER REFILLING TIMES OF DOUBLE BREAK TESTS (REPORT CWAPD−460)

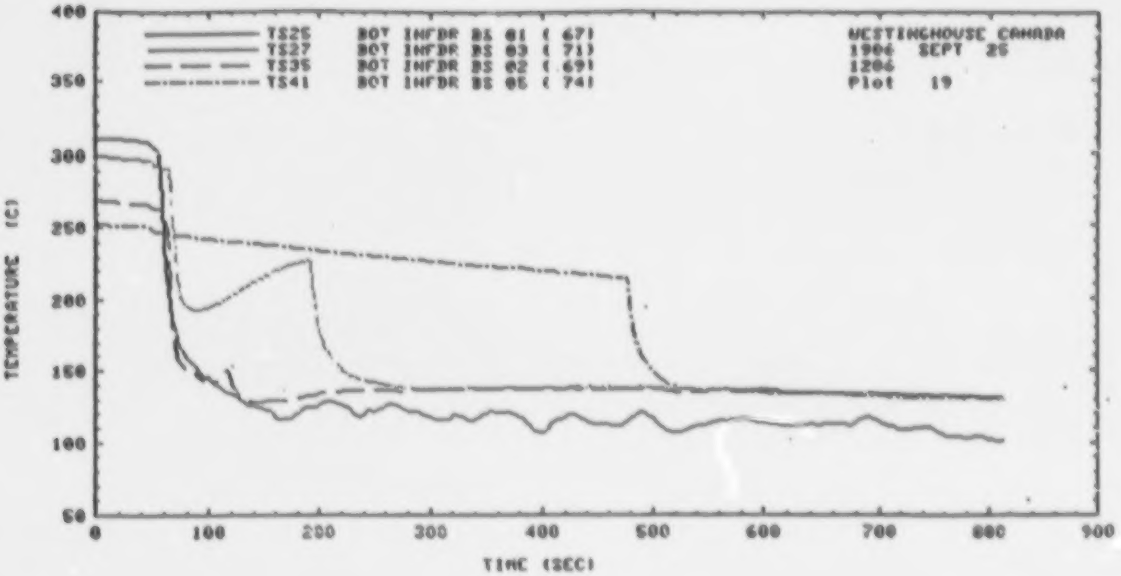


FIGURE 38: FEEDER SURFACE TEMPERATURE CURVES

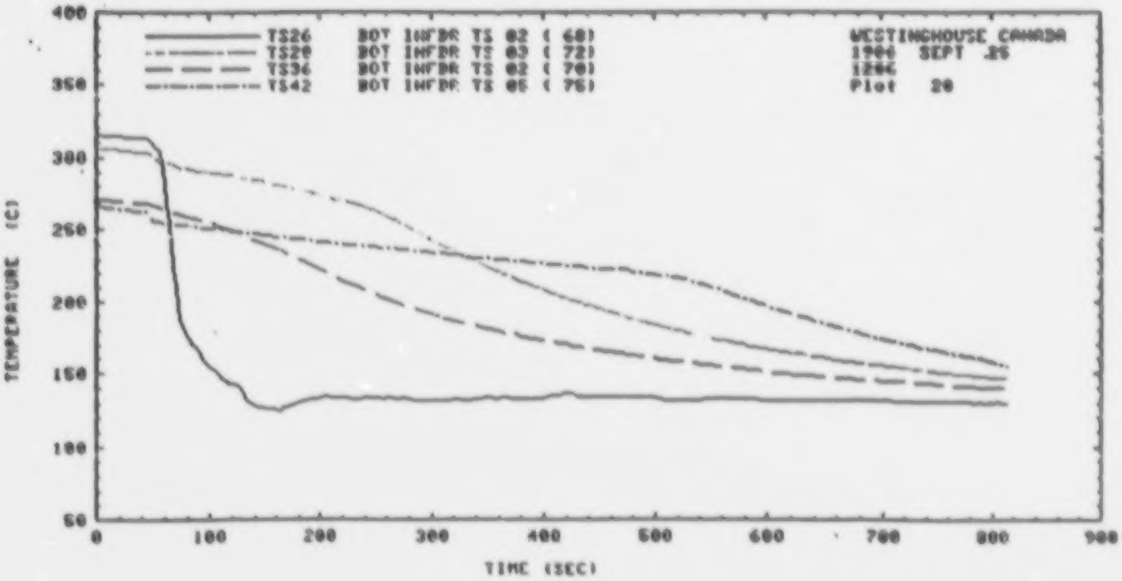


FIGURE 39: FEEDER SURFACE TEMPERATURE CURVES

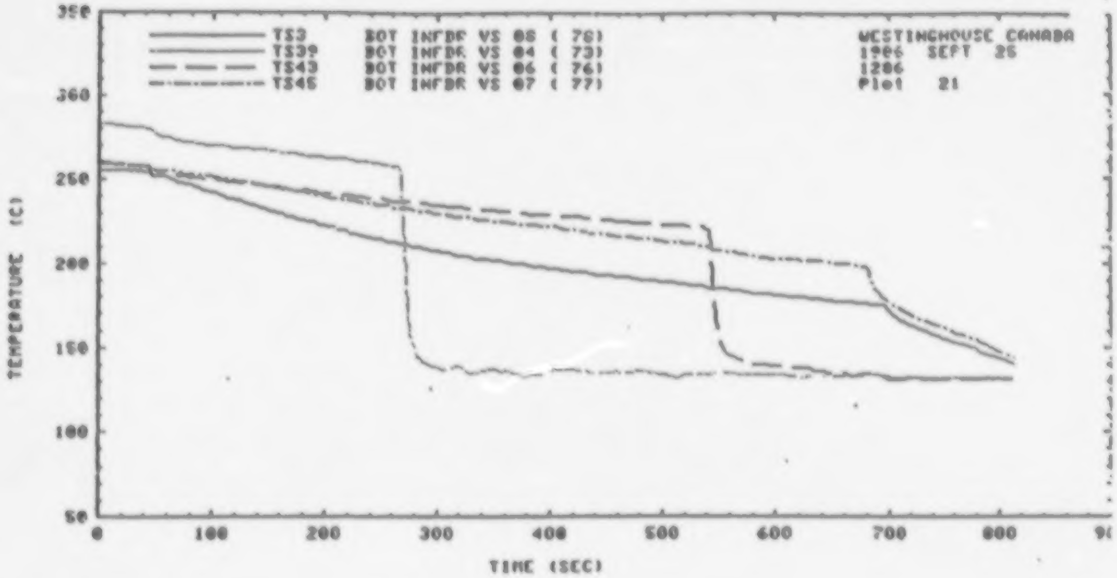


FIGURE 40: FEEDER SURFACE TEMPERATURE CURVES

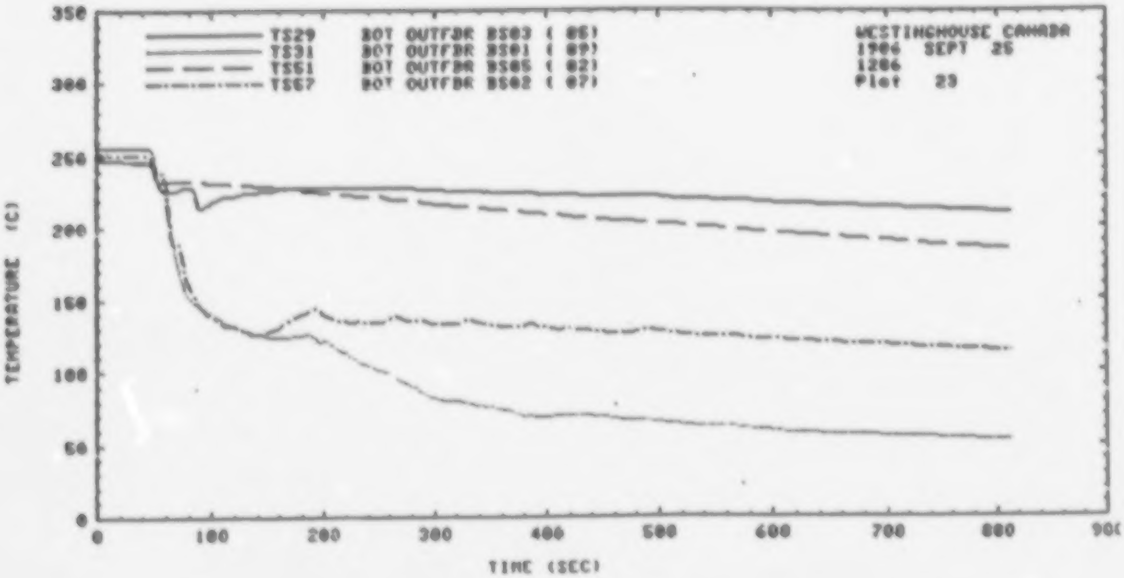


FIGURE 41: FEEDER SURFACE TEMPERATURE CURVES

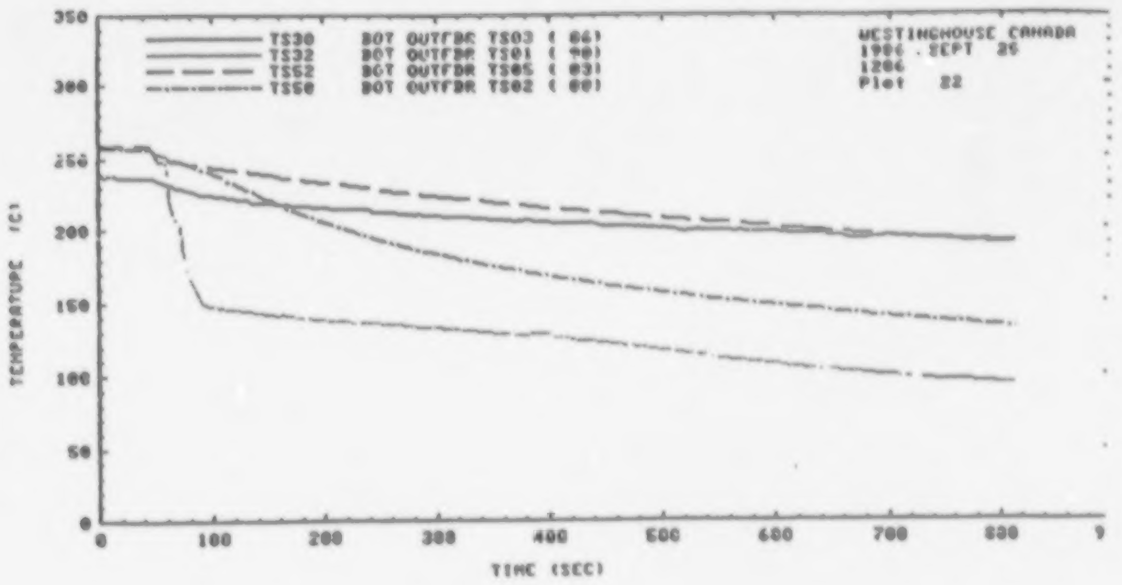


FIGURE 42: FEEDER SURFACE TEMPERATURE CURVES

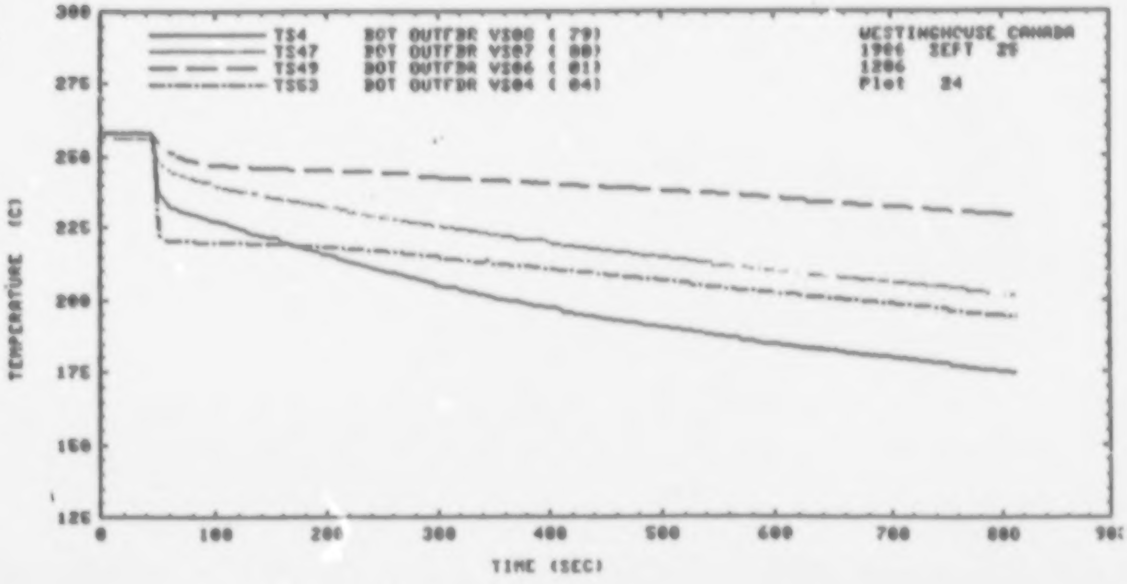


FIGURE 43: FEEDER SURFACE TEMPERATURE CURVES

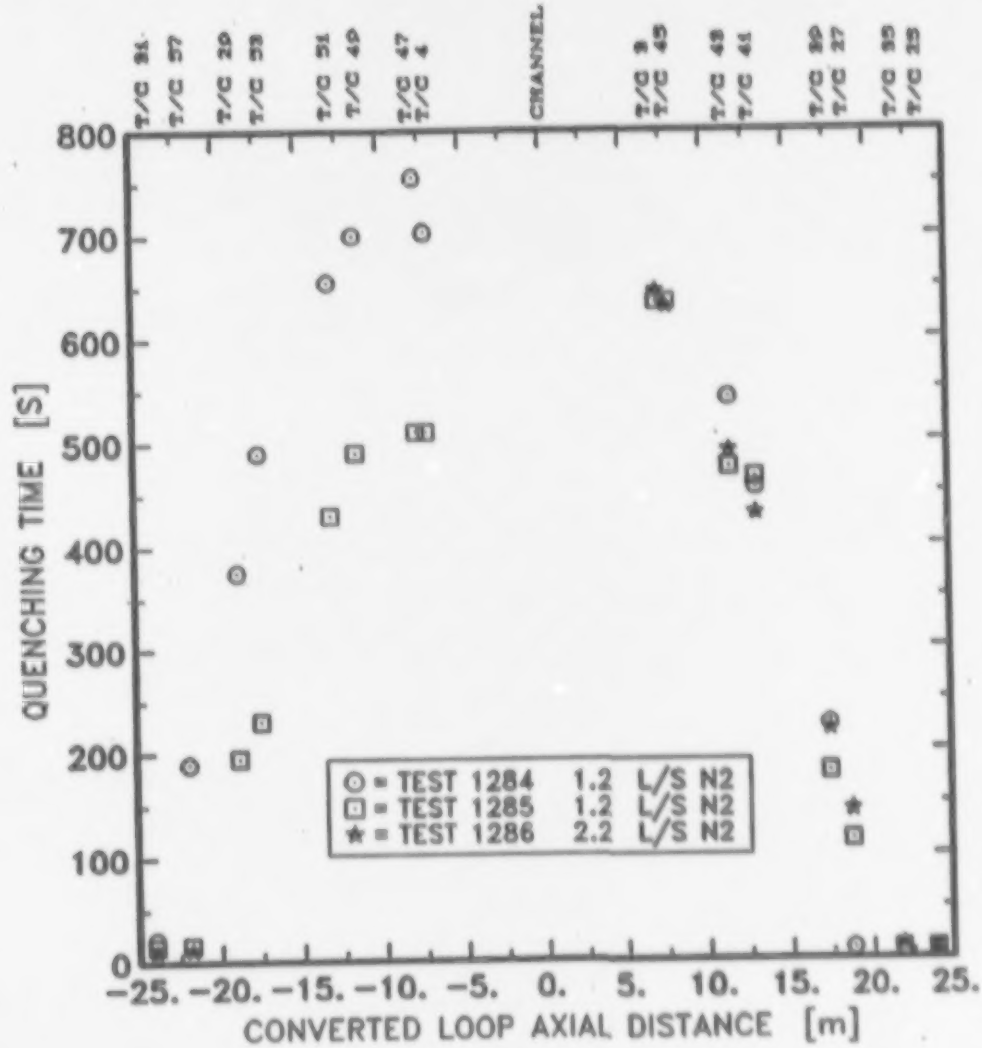


FIGURE 44: EFFECT OF GAS INJECTION ON FEEDER QUENCHING TIMES OF DOUBLE BREAK TESTS (REPORT CWAPD−480)

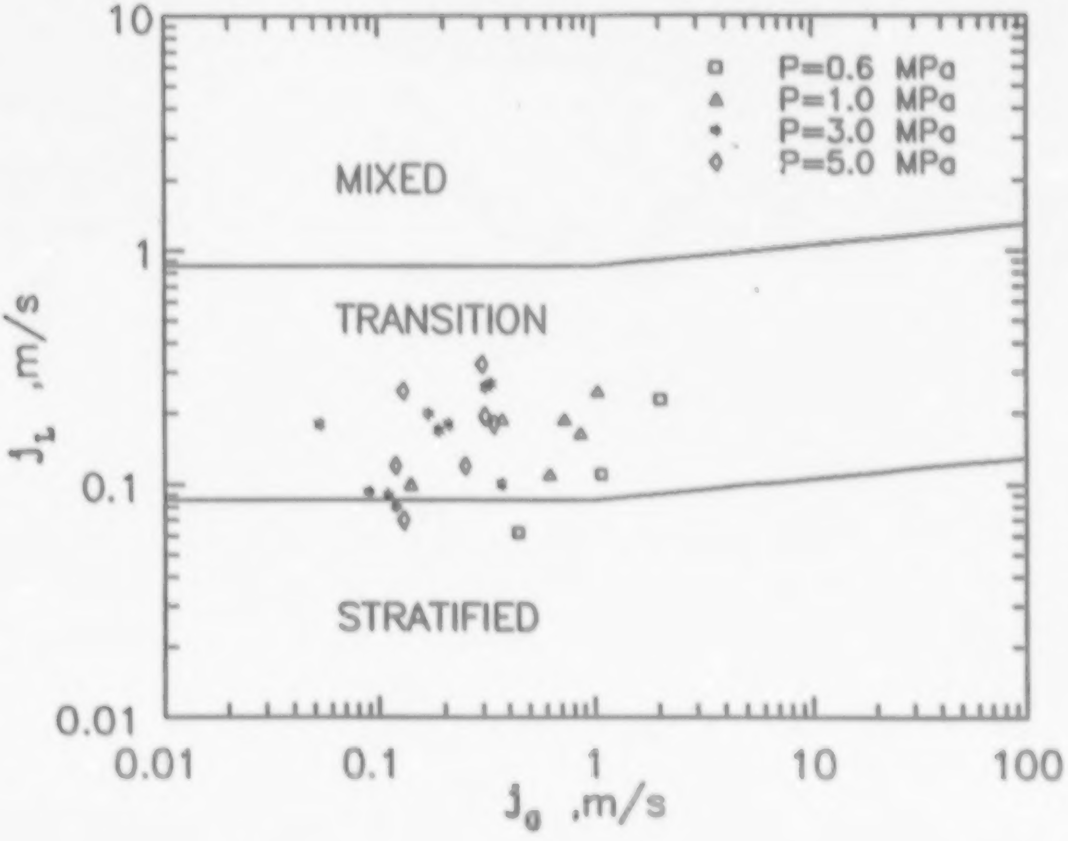
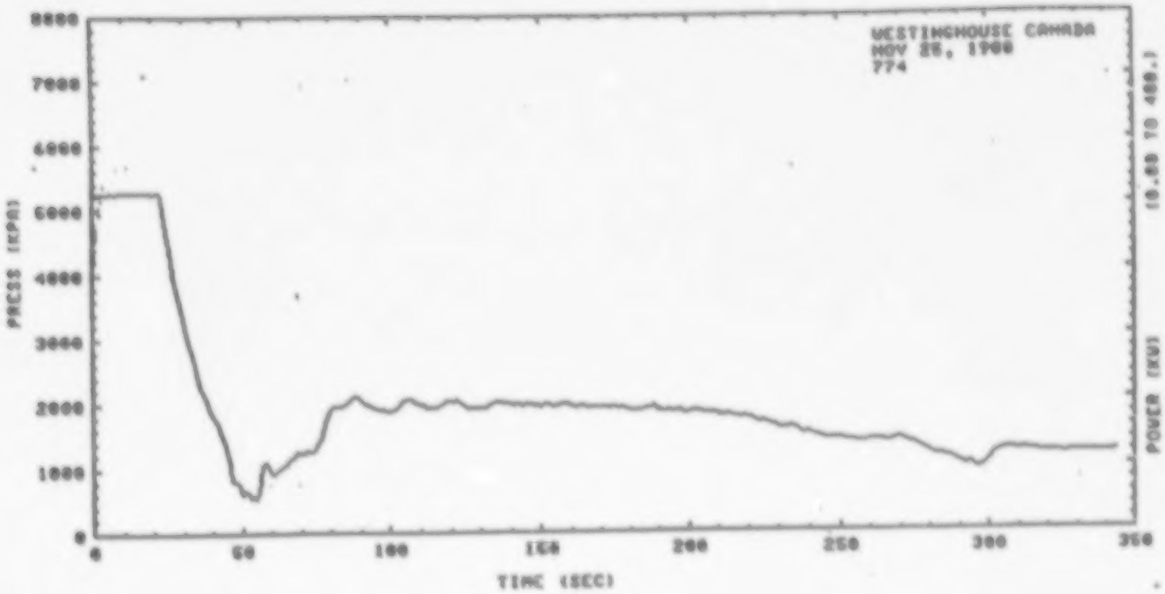
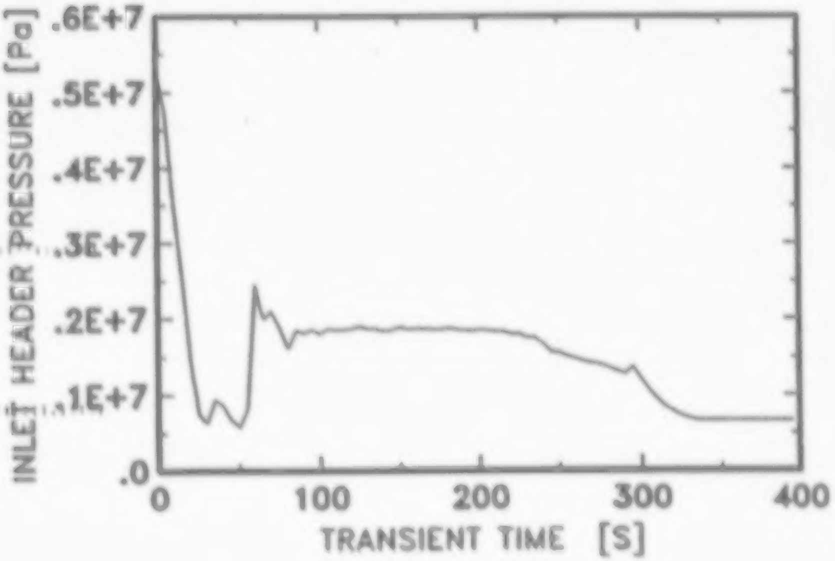


FIGURE 45: COMPARISON OF CWIT FLOW STRATIFICATION RESULTS WITH CATHENA TRANSITION BOUNDARIES

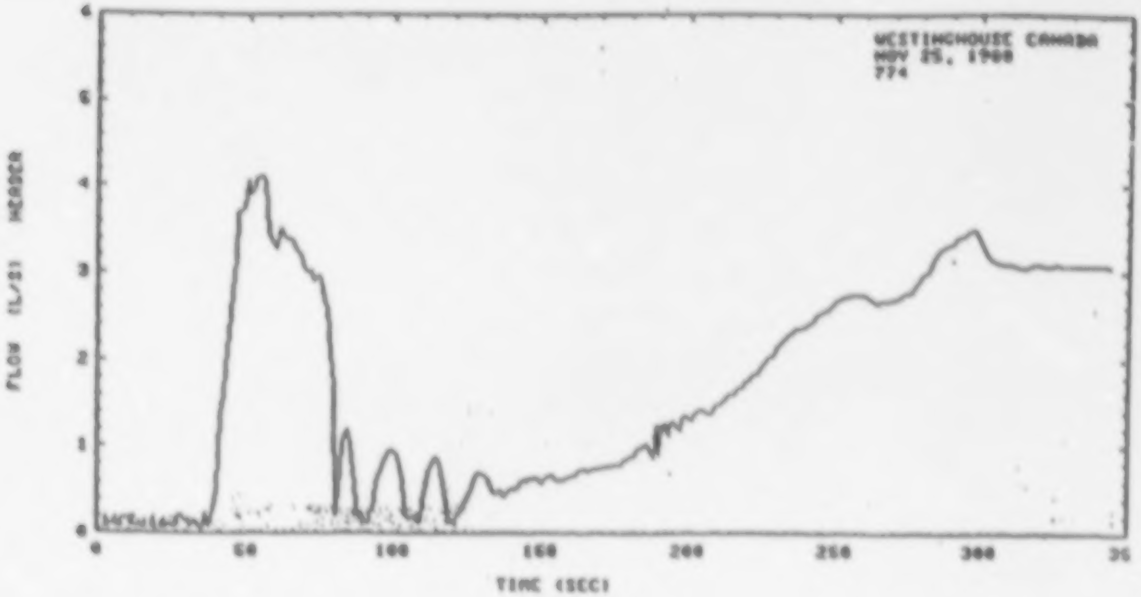


A: EXPERIMENT

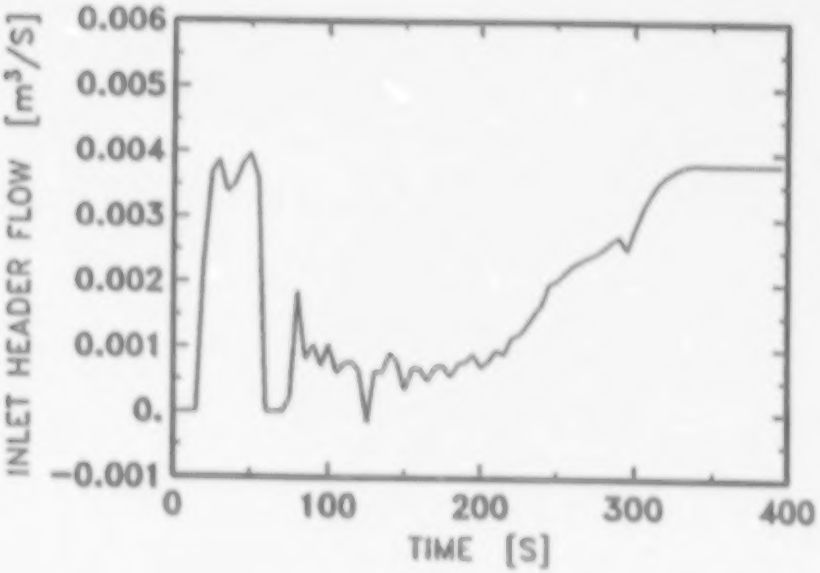


B: CATHENA PREDICTIONS

FIGURE 46: INLET HEADER PRESSURE
TRANSIENTS. CWIT 774

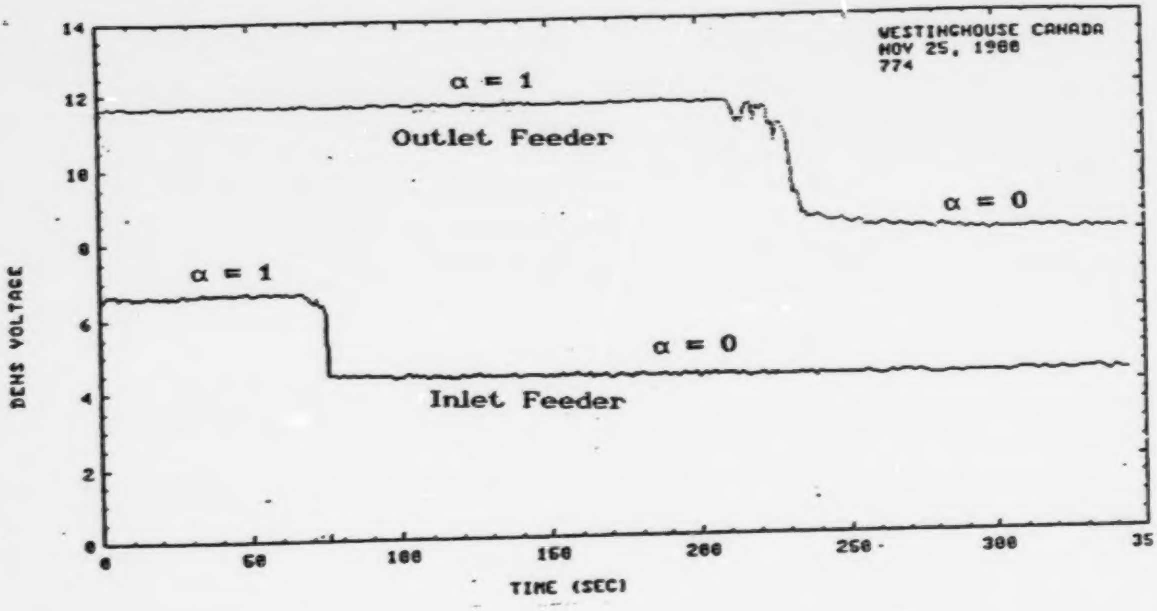


A: EXPERIMENT

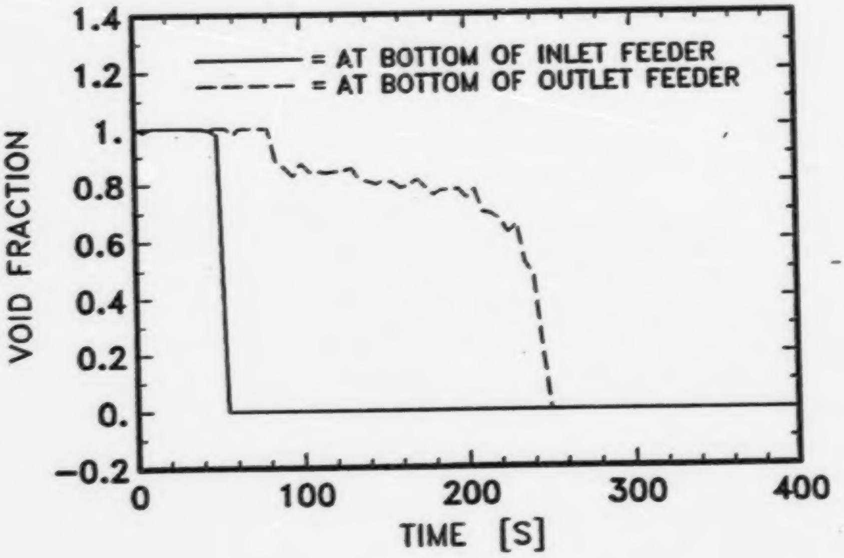


B: CATHENA PREDICTIONS

FIGURE 47: TRANSIENT INLET HEADER FLOW
CWIT 774

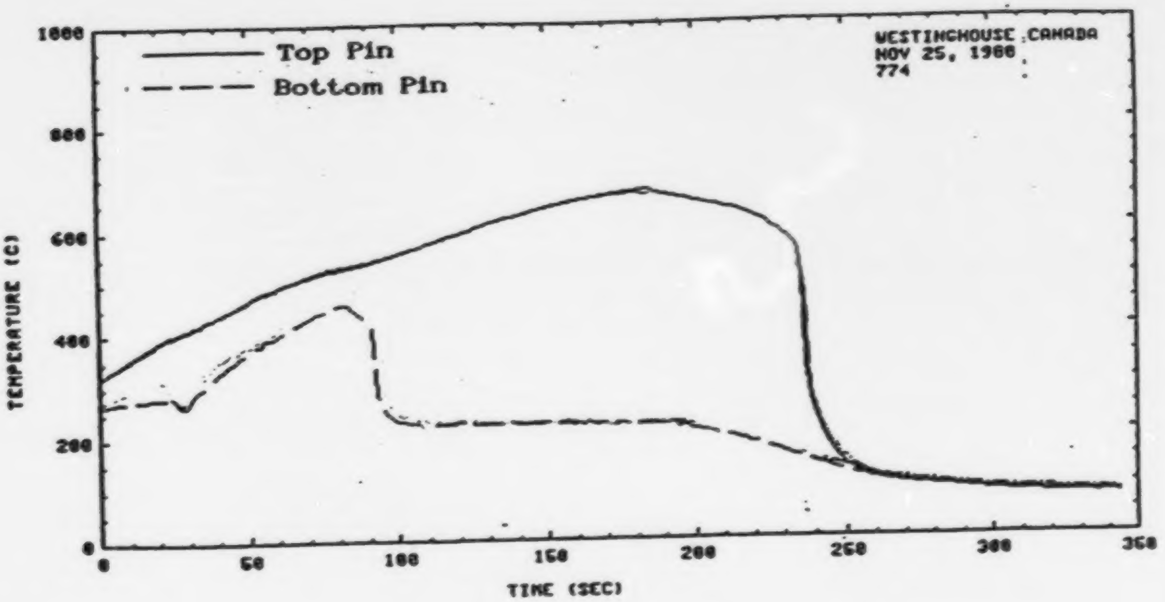


A: EXPERIMENT

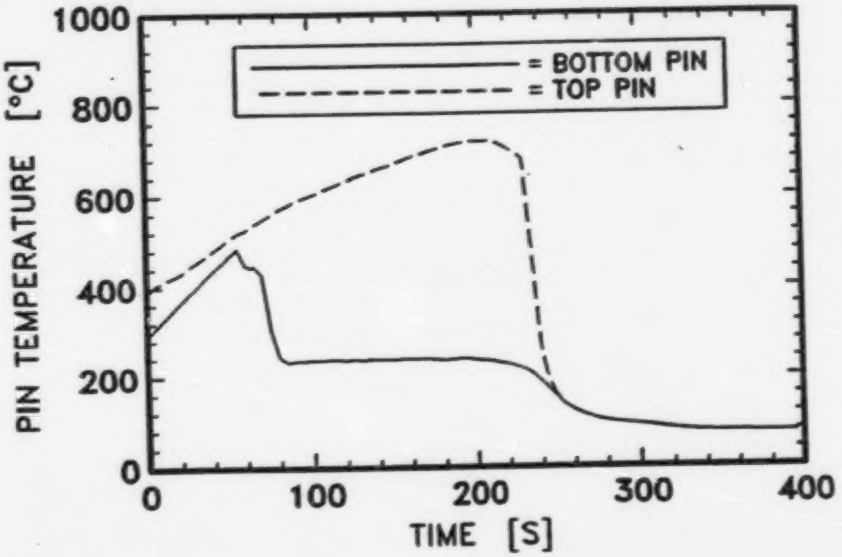


B: CATHENA PREDICTIONS

FIGURE 48: TRANSIENT VOID FRACTION NEAR THE BOTTOM OF INLET AND OUTLET FEEDERS. CWIT 774

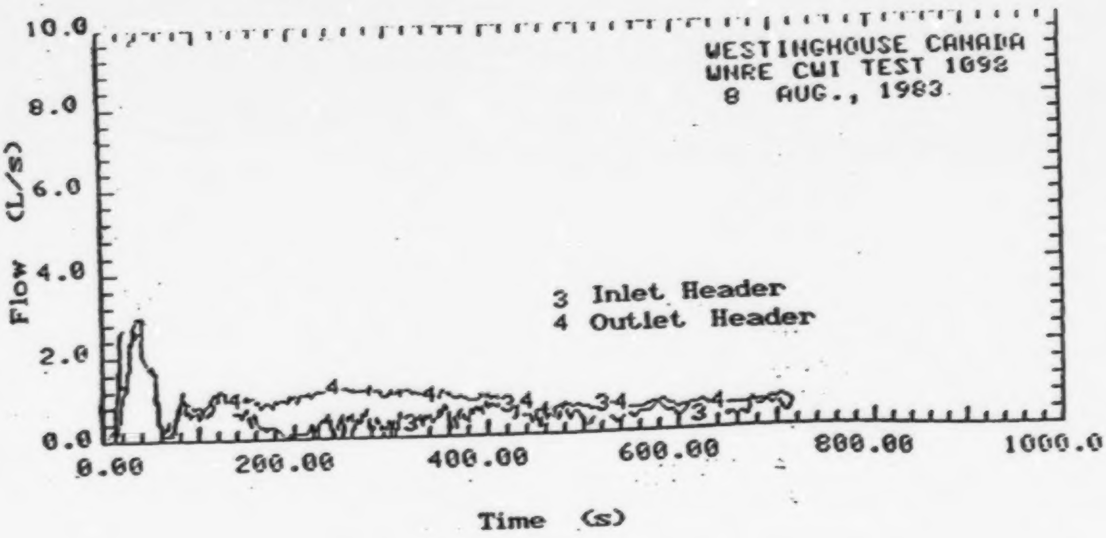


A: EXPERIMENT

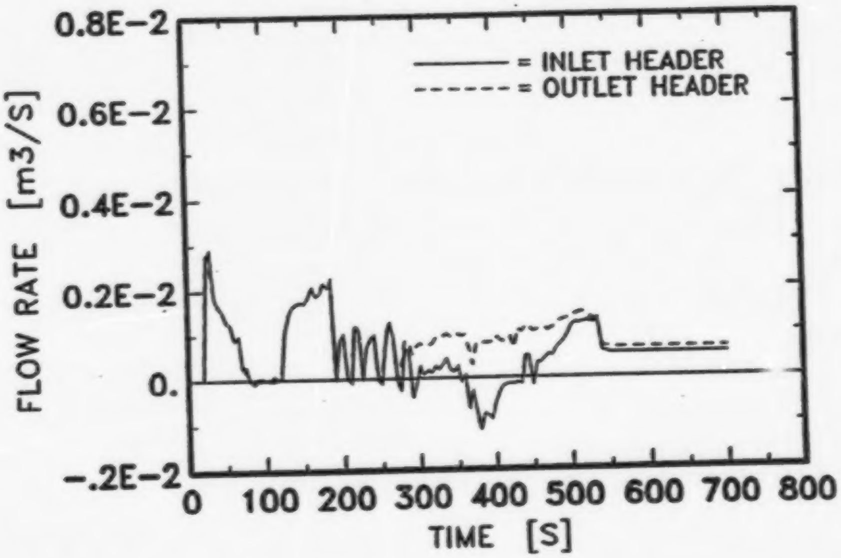


B: CATHENA PREDICTIONS

FIGURE 49: TRANSIENT BOTTOM AND TOP PIN TEMPERATURES AT 4.75 m FROM CHANNEL INLET.
CWIT 774

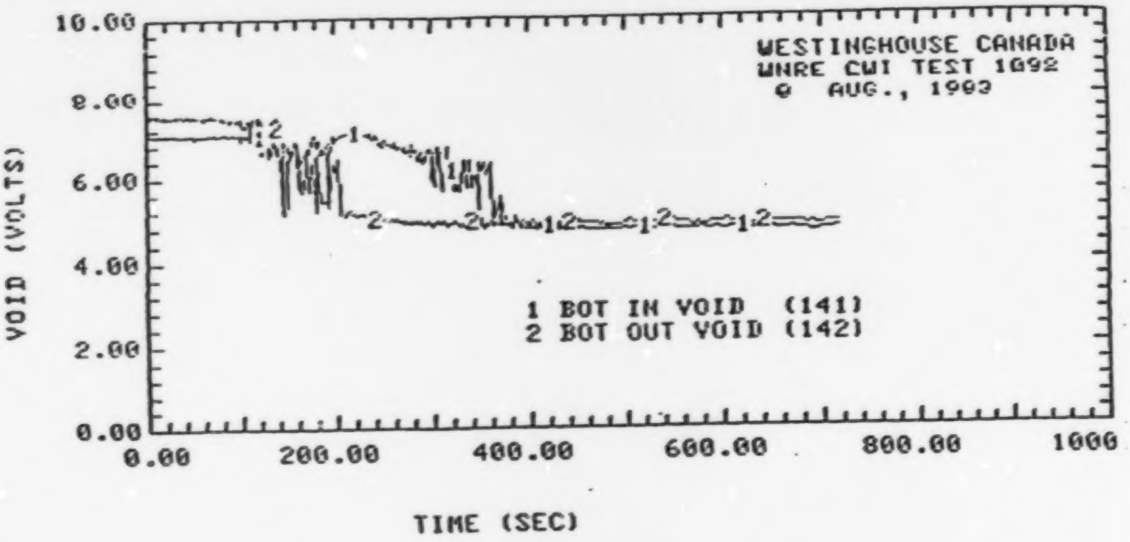


A: EXPERIMENT

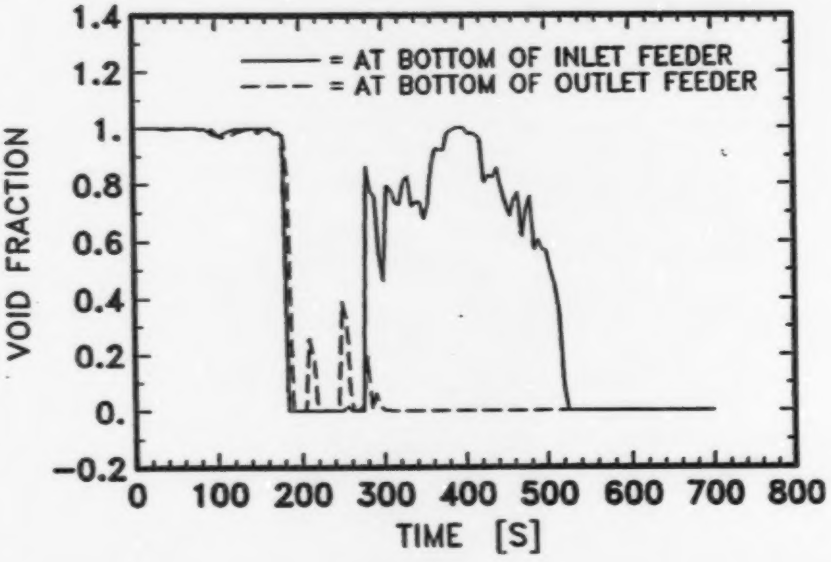


B: CATHENA PREDICTIONS

FIGURE 52: TRANSIENT INLET AND OUTLET HEADER FLOW RATES. CWIT 1098



A: EXPERIMENT



B: CATHENA PREDICTIONS

FIGURE 53: TRANSIENT VOID FRACTION
NEAR THE BOTTOM OF INLET AND
OUTLET FEEDERS.
CWIT 1098

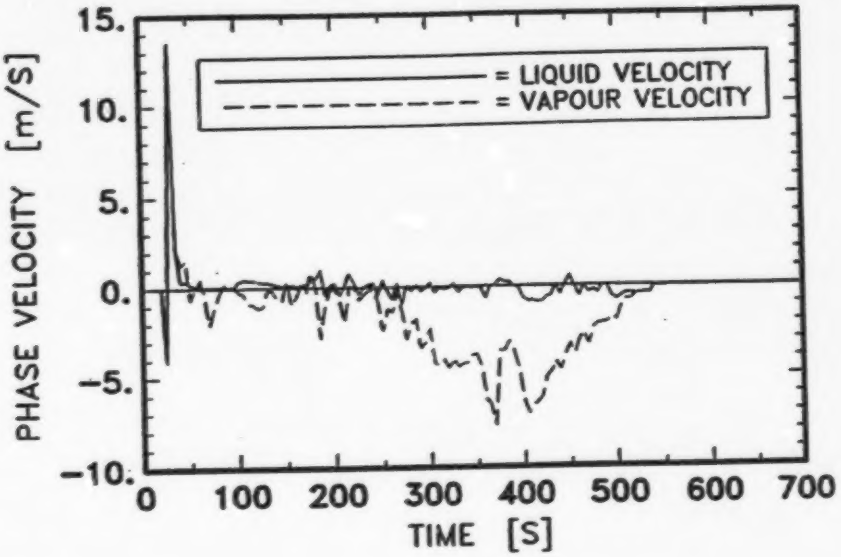
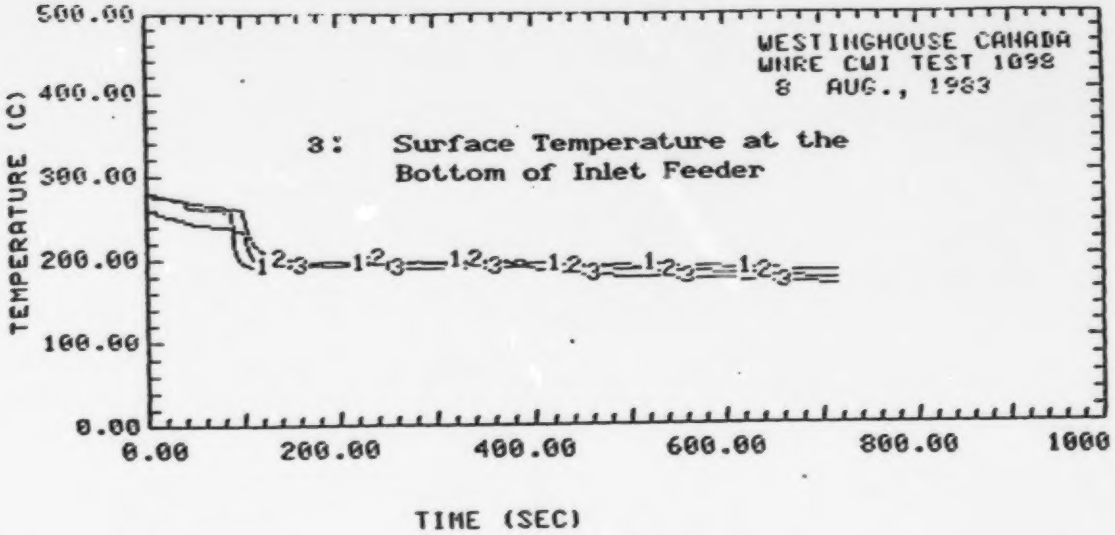
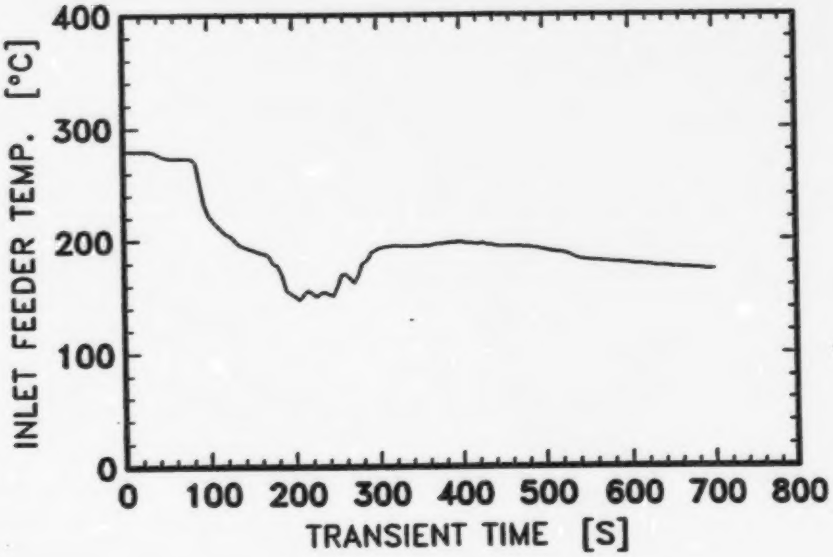


FIGURE 54: TRANSIENT VAPOUR AND LIQUID VELOCITIES NEAR THE BOTTOM OF INLET FEEDER CWIT 1098

CATHENA PREDICTIONS

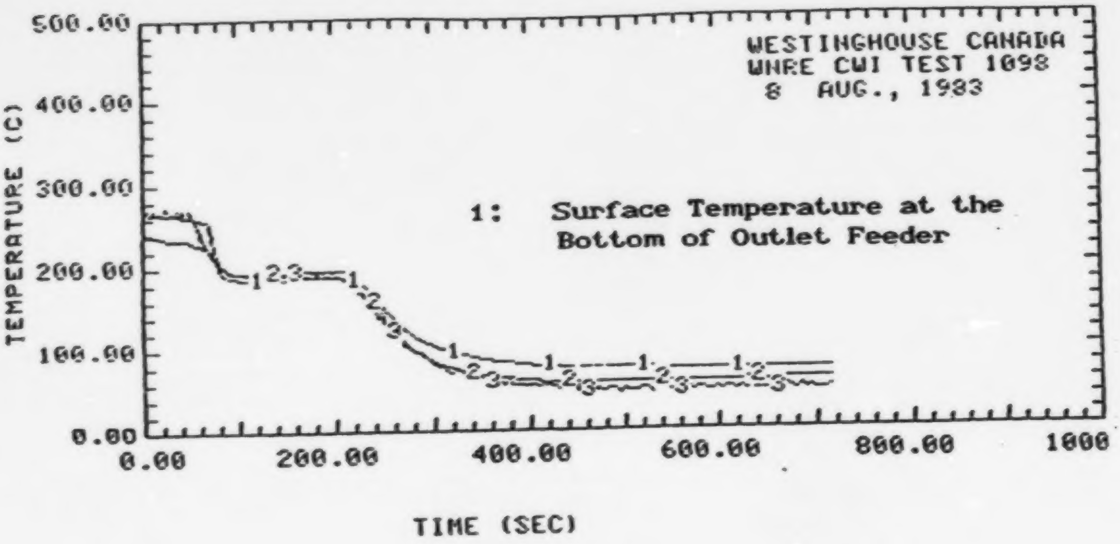


A: EXPERIMENT

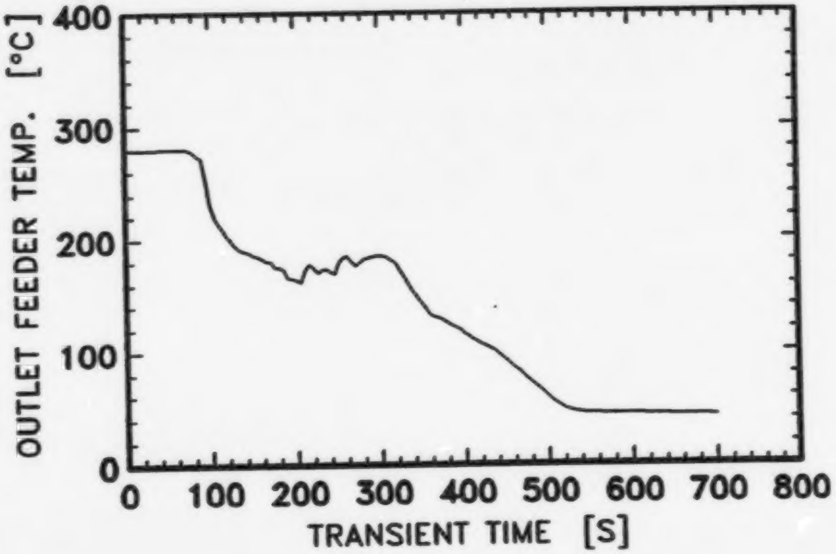


B: CATHENA PREDICTIONS

FIGURE 55: SURFACE TEMPERATURE AT
THE BOTTOM OF INLET FEEDER.
CWIT 1098

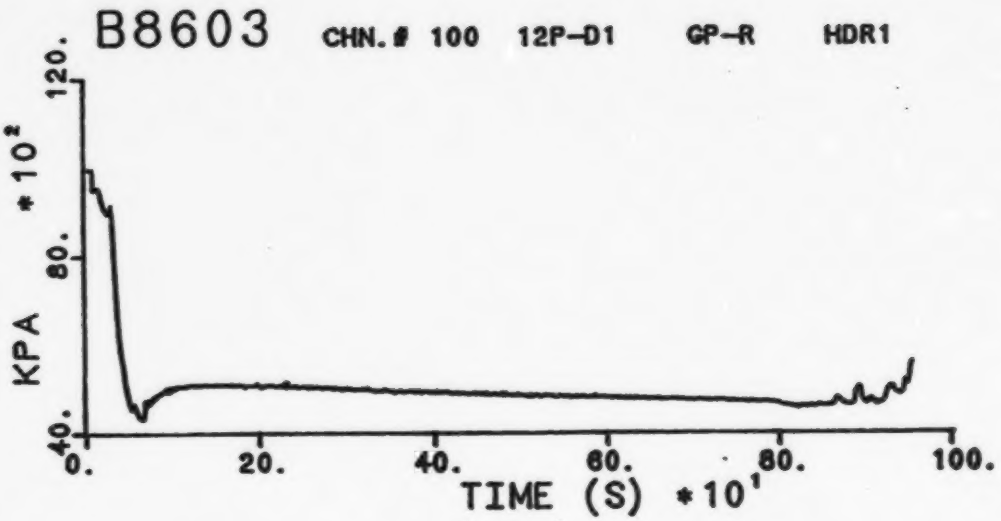


A: EXPERIMENT

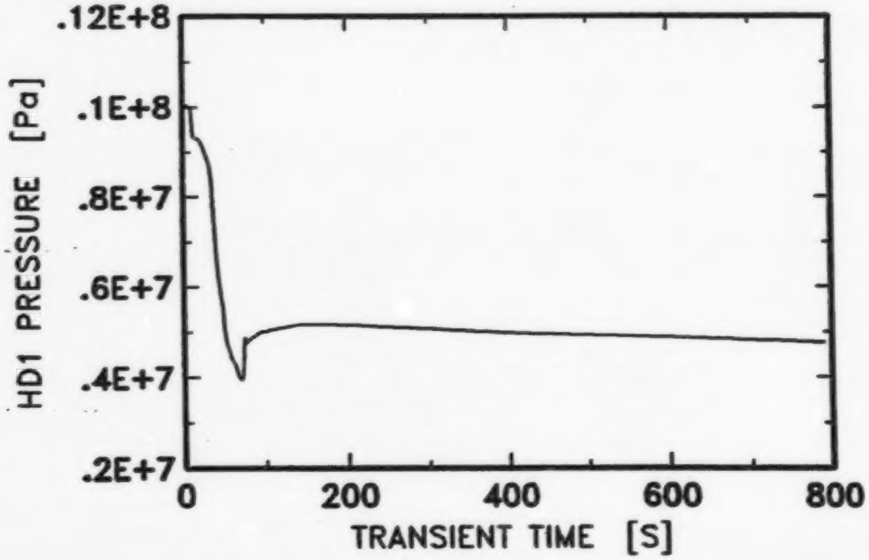


B: CATHENA PREDICTIONS

FIGURE 56: SURFACE TEMPERATURE AT
THE BOTTOM OF OUTLET FEEDER
CWIT 1098

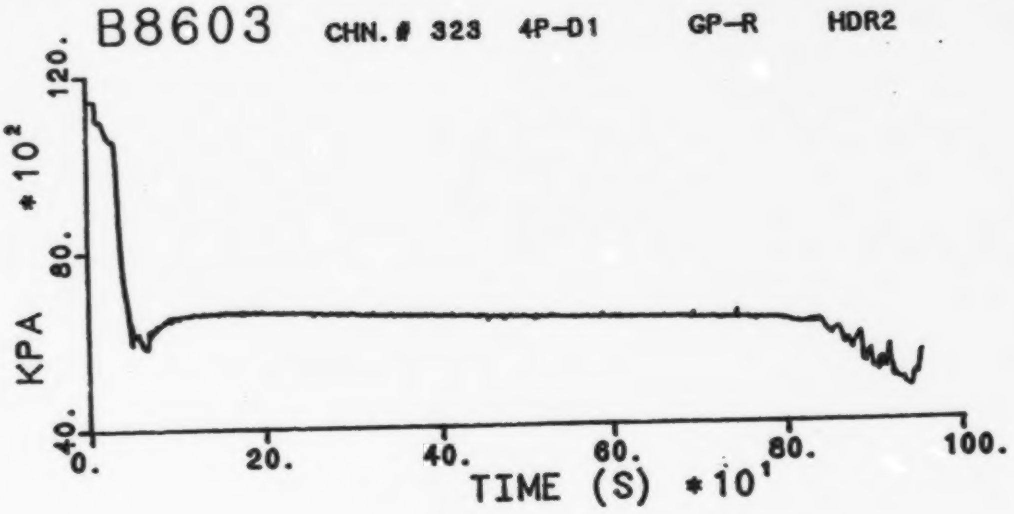


A: EXPERIMENT

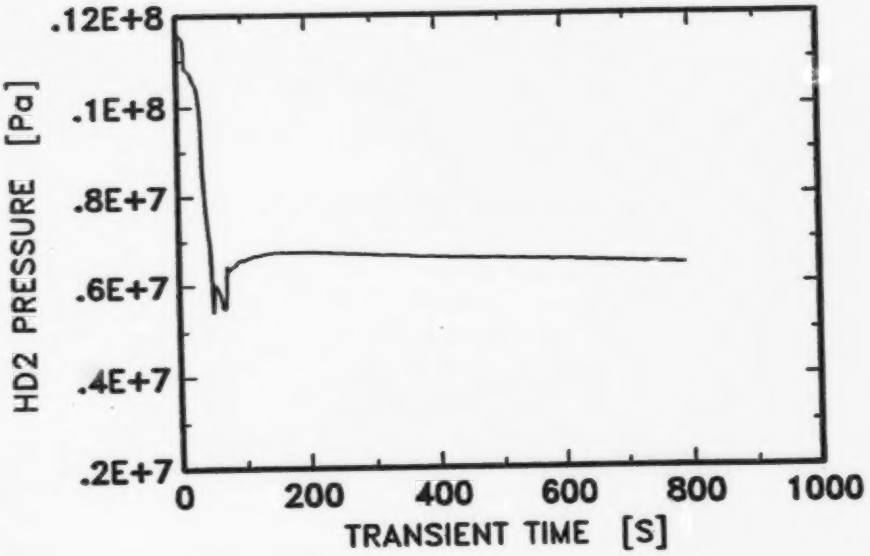


B: CATHENA PREDICTIONS

FIGURE 57: HD1 PRESSURE TRANSIENTS
RD-14 B8603

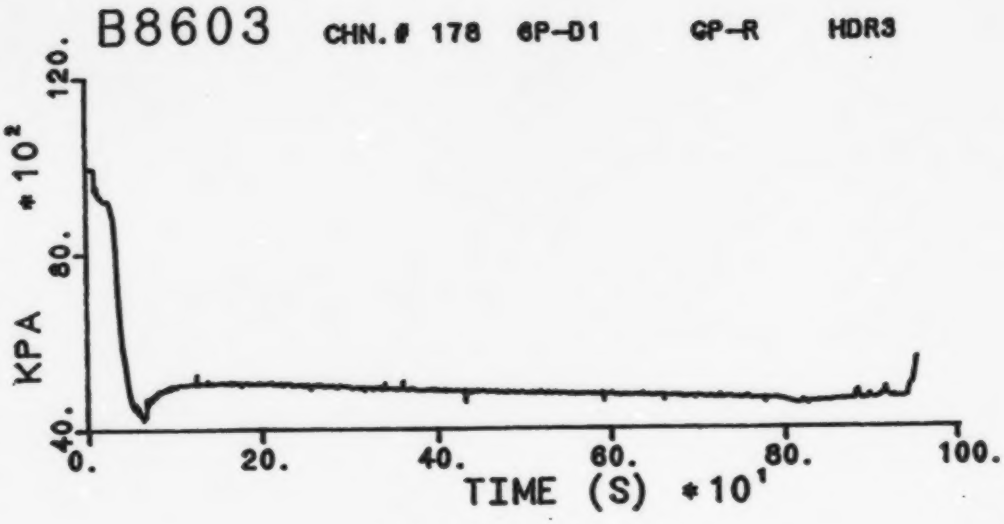


A: EXPERIMENT

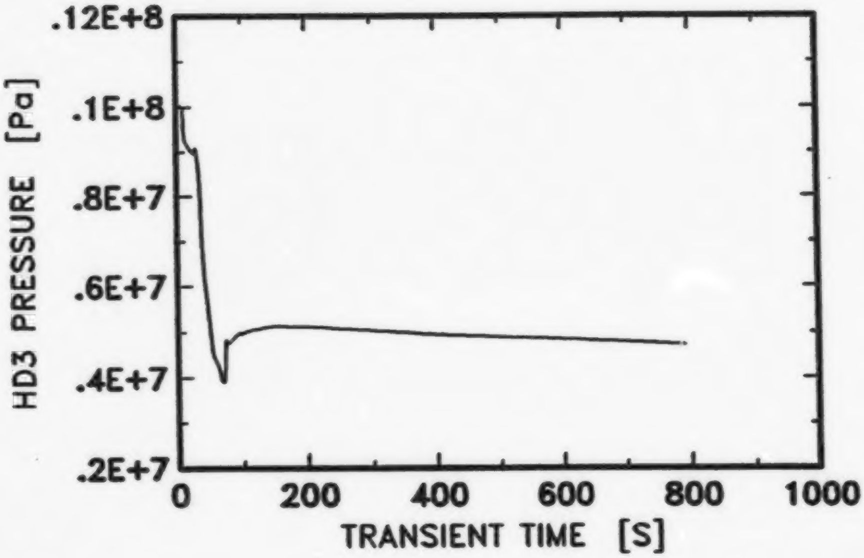


B: CATHENA PREDICTIONS

FIGURE 58: HD2 PRESSURE TRANSIENTS
RD-14 B8603

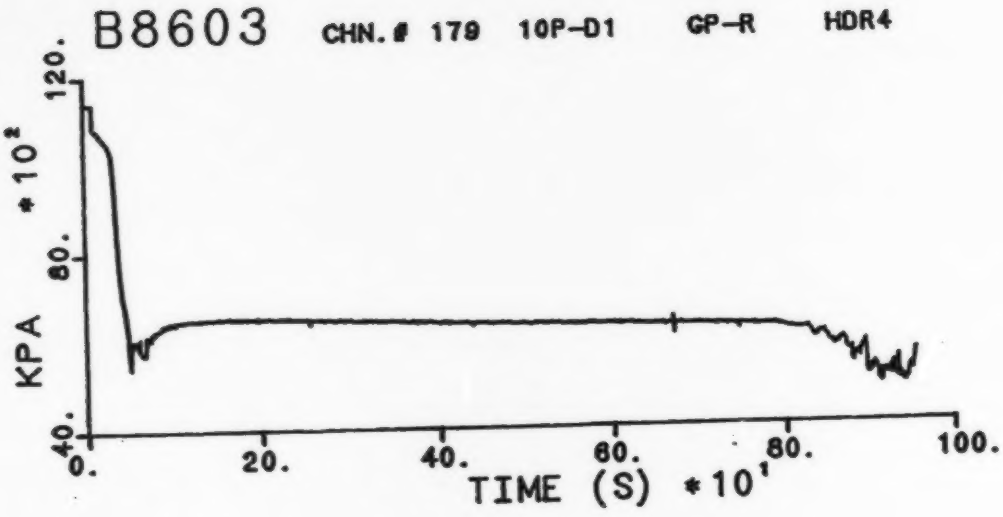


A: EXPERIMENT

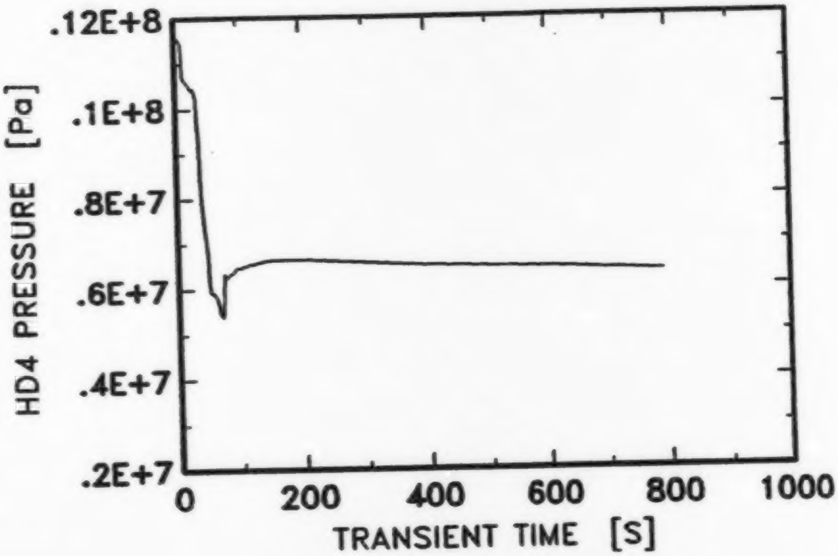


B: CATHENA PREDICTIONS

FIGURE 59: HD3 PRESSURE TRANSIENTS
RD-14 B8603

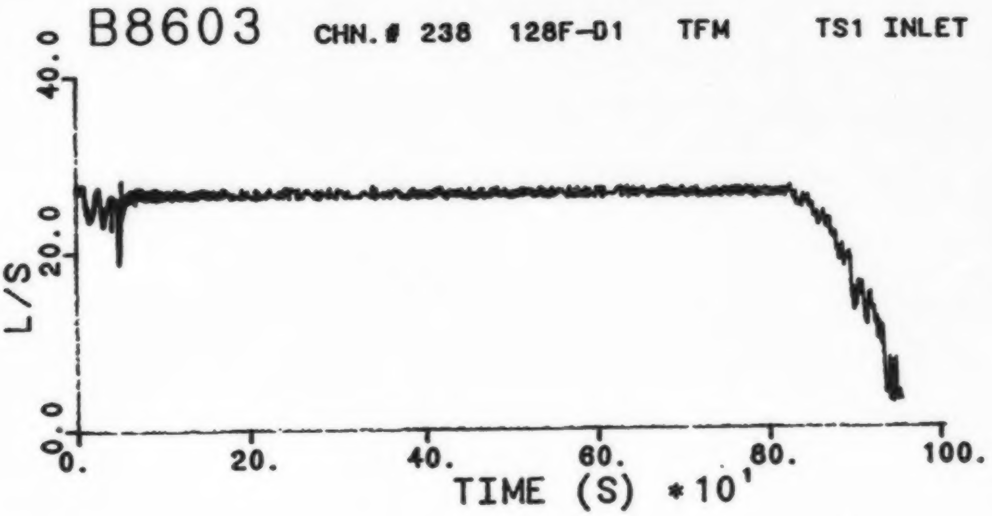


A: EXPERIMENT

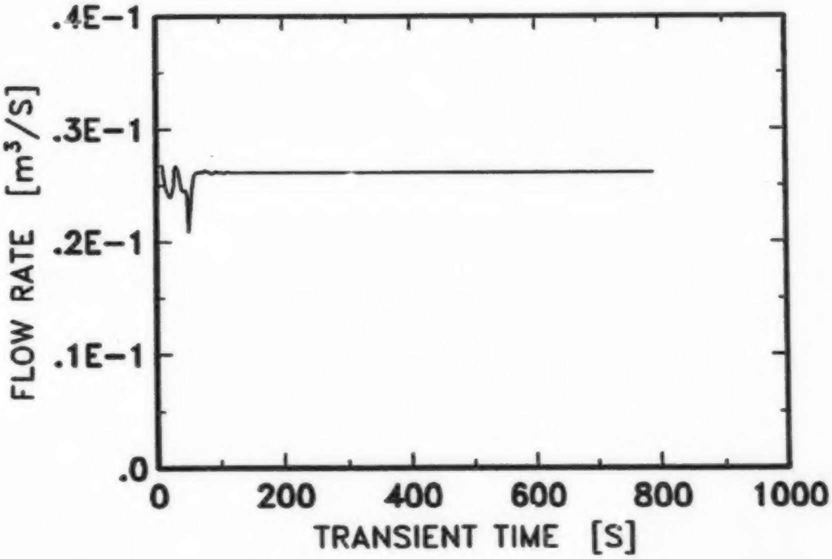


B: CATHENA PREDICTIONS

FIGURE 60: HD4 PRESSURE TRANSIENTS
RD–14 B8603

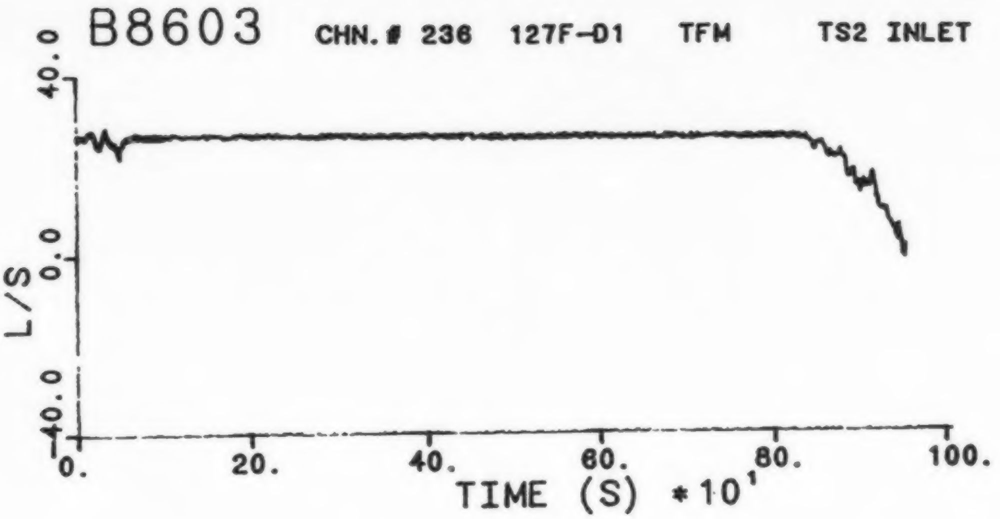


A: EXPERIMENT

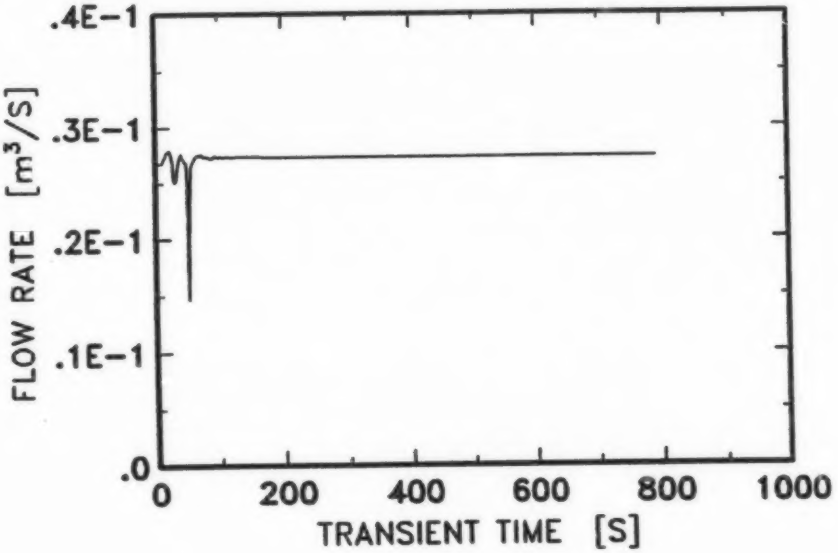


B: CATHENA PREDICTIONS

FIGURE 61: TRANSIENT INLET FLOW
RATE TO CHANNEL TS1
RD-14 B8603

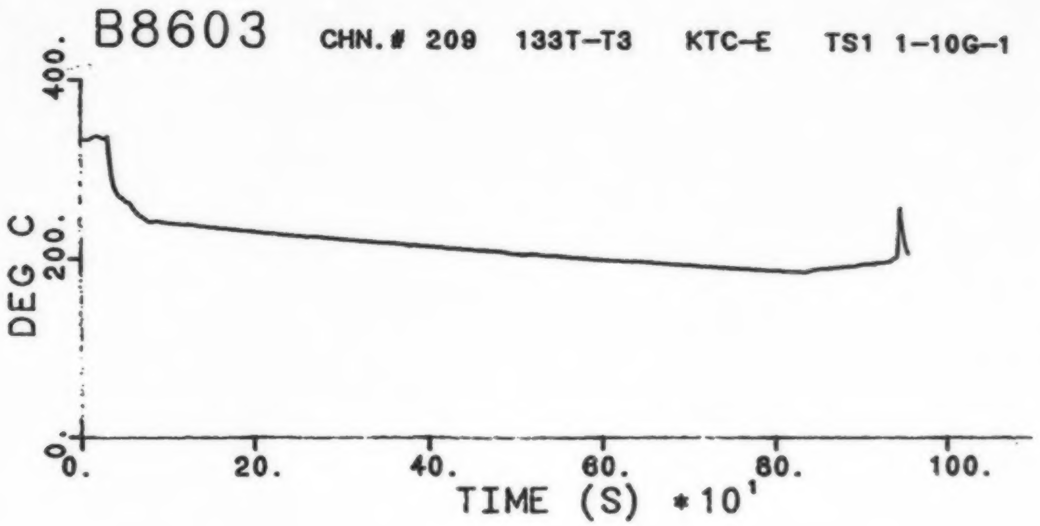


A: EXPERIMENT

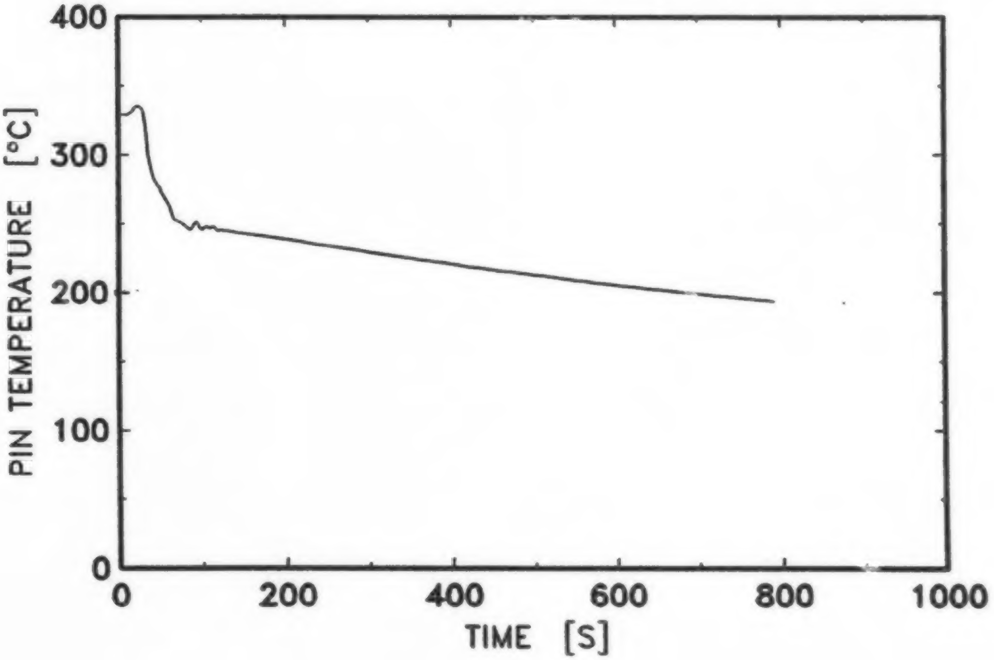


B: CATHENA PREDICTIONS

FIGURE 62: TRANSIENT INLET FLOW
TO CHANNEL TS2.
RD-14 B8603

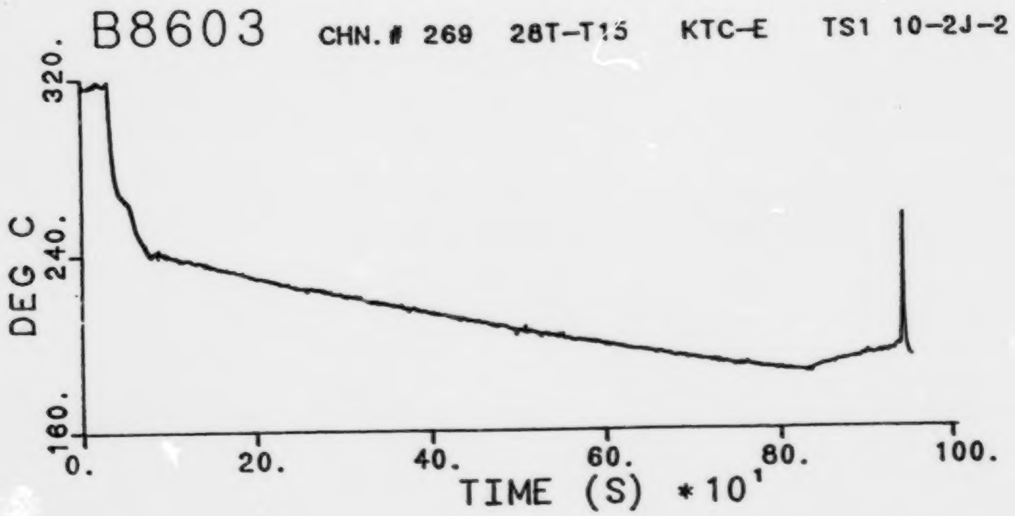


A: EXPERIMENT

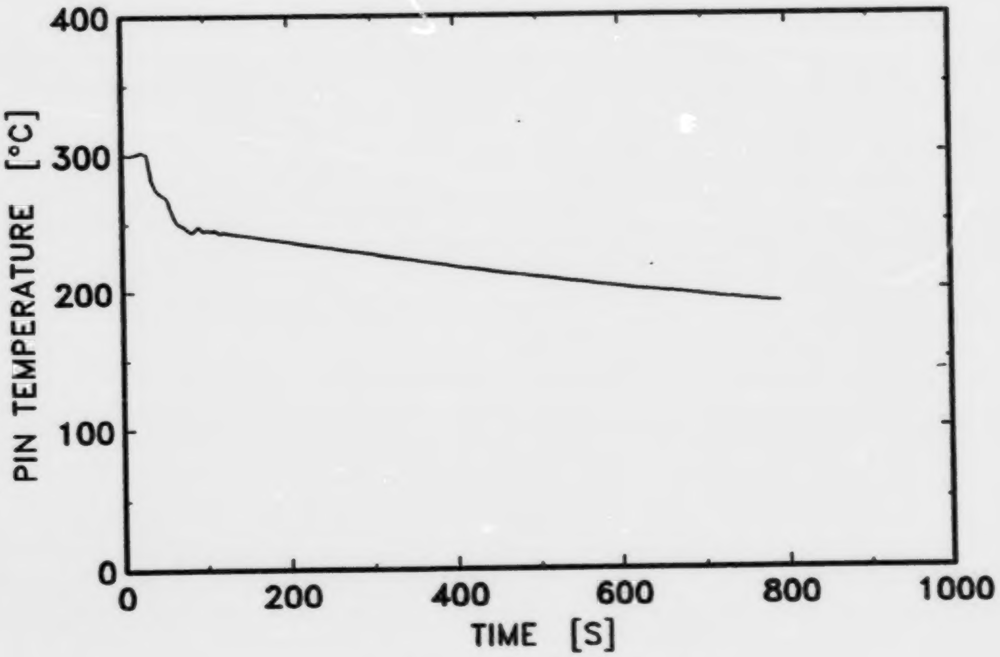


B: CATHENA PREDICTIONS

FIGURE 63: TRANSIENT TOP PIN TEMPERATURE
AT 5 m FROM INLET OF CHANNEL TS1.
RD-14 B8603

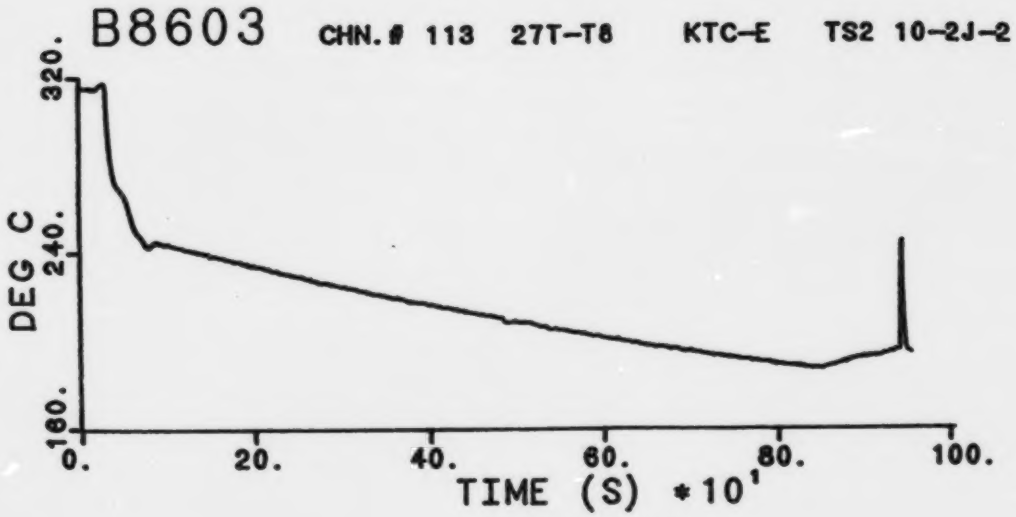


A: EXPERIMENT

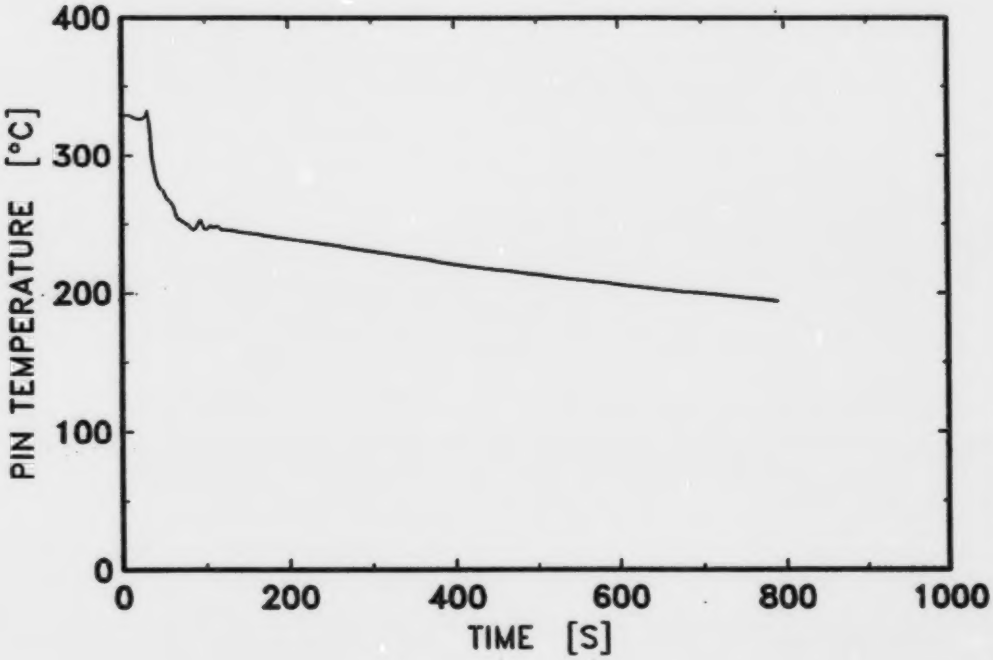


B: CATHENA PREDICTIONS

FIGURE 64: TRANSIENT BOTTOM PIN TEMP.
AT 0.5 m FROM INLET OF CHANNEL TS1.

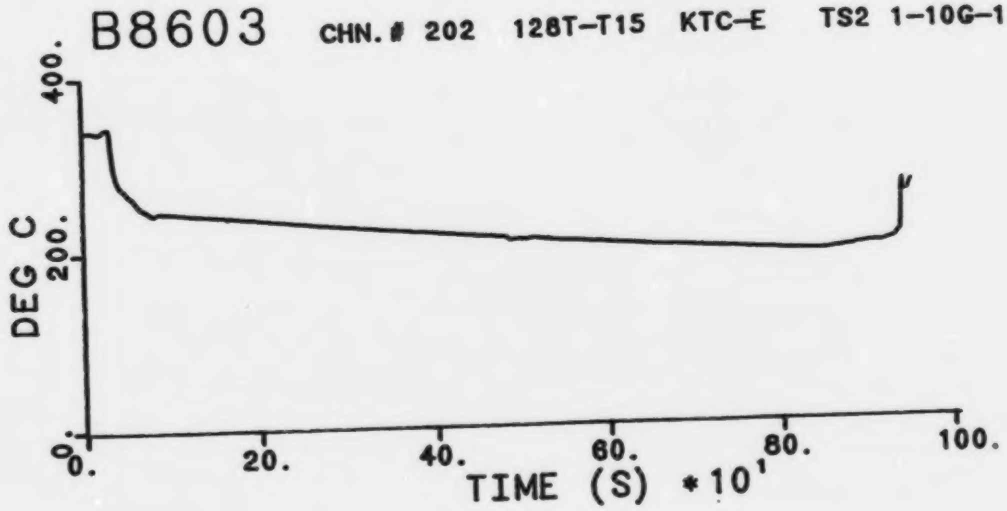


A: EXPERIMENT

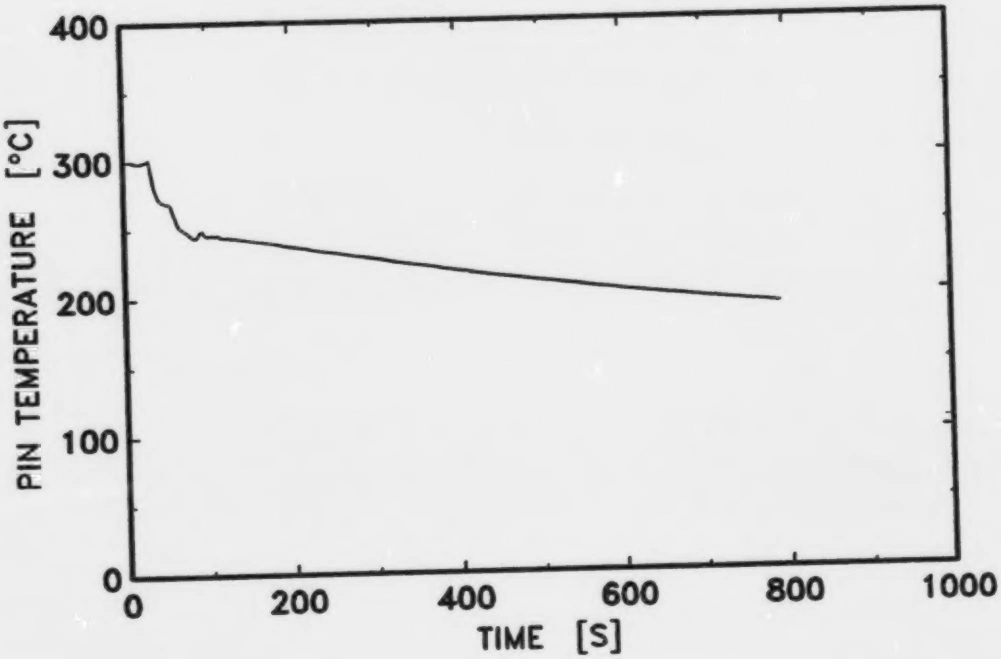


B: CATHENA PREDICTIONS

FIGURE 65: TRANSIENT TOP PIN TEMP.
AT 5 m FROM INLET OF CHANNEL TS2.
RD-14 B8603



A: EXPERIMENT



B: CATHENA PREDICTIONS

FIGURE 66: TRANSIENT BOTTOM PIN TEMP.
AT 0.5 m FROM INLET OF CHANNEL TS2.
RD-14 B8603

APPENDIX A

FEEDER QUENCH AND REFILLING TIME TABLES

Table A1: Feeder Quench and Refilling Times. Tests of Report CWAPD-480
i – Single (Bottom) Channel Tests

Test No.	Channel power (kw)	Break Size Inlet/-Outlet %	Initial Feeder Temperature (°C)		First Refilled Feeder	Other Conditions	Quench Times (s) / Refilling Times (s)																							
			In T/C 26	Out T/C 32			Outlet Feeder Thermocouples												Inlet Feeder Thermocouples											
							T/C 31	T/C 32	T/C 57	T/C 58	T/C 29	T/C 30	T/C 53	T/C 51	T/C 52	T/C 49	T/C 47	T/C 4	T/C 3	T/C 45	T/C 43	T/C 41	T/C 42	T/C 39	T/C 27	T/C 28	T/C 35	T/C 36	T/C 25	T/C 26
1267	0	100/100	268	268	IN		10 475	10 –	13 465	310 –	310 460	315 –	315 420	300 395	295 400	302 400	298 370	295 370	140 285	175 285	145 275	130 275	150 280	80 270	50 270	210 270	20 260	200 260	20 180	261 190
1268	0	100/100	355	300	IN		15 –	27 –	15 –	268 –	270 –	705 –	705 815	688 800	685 800	693 795	682 770	680 770	385 647	508 643	613 645	235 643	458 643	245 645	85 640	455 605	10 600	450 600	10 585	10 580
1269	0	100/100	270	260	IN		18 –	20 –	18 –	110 –	137 –	345 –	345 –	335 –	330 –	335 425	330 395	325 395	180 310	180 310	163 300	160 297	170 305	110 298	88 295	167 297	35 277	145 282	10 230	25 233
1275	0	100/70	360	295	IN		15 –	20 –	610 –	110 –	115 –	185 –	620 –	605 –	605 –	615 725	610 700	598 700	275 600	430 600	265 545	170 545	475 545	215 540	43 537	485 537	7 493	115 495	7 443	43 446
1277	0	100/70	367	308	IN	Orifice at Inlet Feeder	25 –	25 –	26 –	100 –	85 –	128 –	122 –	130 –	660 –	660 750	653 740	650 740	370 650	470 650	256 585	180 580	492 582	185 580	20 575	490 575	10 560	120 560	10 470	20 470
1278	0	100/100	345	300	IN		10 –	22 –	25 –	130 –	128 –	530 –	200 –	520 –	520 –	523 –	518 620	515 620	255 500	385 500	230 450	140 450	350 452	180 448	80 448	140 450	8 432	120 440	8 130	40 130
1280	50	17.9/17.9	345	280	OUT		30 320	30 380	40 340	390 400	40 420	380 420	95 440	130 520	290 500	170 520	200 530	180 530	570 940	572 943	580 955	572 –	575 –	420 –	12 –	600 –	10 –	600 –	10 –	14 –

– No Quenching or No Complete Refilling
x Faulty Thermocouple
* Showed No Water Penetration to the Channel During the Entire Time of Testing
Note: All times indicated are estimated from the initiation of water injection to the headers.

Table A1: Feeder Quench and Refilling Times. Tests of Report CWAPD-480
i – Single (Bottom) Channel Tests (continued)

Test No.	Channel power (kw)	Break Size Inlet/-Outlet %	Initial Feeder Temperature (°C)		First Refilled Feeder	Other Conditions	Quench Times (s) / Refilling Times (s)																							
							Outlet Feeder Thermocouples												Inlet Feeder Thermocouples											
			In T/C 26	Out T/C 32			T/C 31	T/C 32	T/C 57	T/C 58	T/C 29	T/C 30	T/C 53	T/C 51	T/C 52	T/C 49	T/C 47	T/C 4	T/C 3	T/C 45	T/C 43	T/C 41	T/C 42	T/C 39	T/C 27	T/C 28	T/C 35	T/C 36	T/C 25	T/C 26
1283	50	17.9/17.9	350	290	OUT		25	30	30	405	50	400	65	75	270	82	202	180	560	563	573	18	570	578	15	590	10	585	10	13
							150	390	370	400	450	440	450	490	490	490	500	500	–	–	–	–	–	–	–	–	–	–	–	–
1290	0	6.4/6.4	350	283	OUT		20	30	23	420	30	420	40	52	410	75	118	120	460	470	440	430	420	280	22	400	7	390	7	7
							40	40	80	420	520	530	540	610	420	610	655	660	–	–	–	–	–	–	–	–	925	–	680	–
1291	0	100/100	252	200	IN		22	20	22	279	30	270	190	295	305	295	300	170	280	280	270	260	270	125	100	340	46	250	10	28
							–	–	–	–	–	–	–	–	–	–	470	470	410	410	395	398	400	392	395	395	385	388	360	364
1292	0	100/20	355	290	OUT		2	15	2	87	25	100	45	35	115	55	70	70	175	178	195	182	183	198	195	211	13	208	13	210
							65	87	90	106	104	130	105	150	155	160	160	160	265	265	265	273	273	295	315	300	315	315	315	315
1284	50	17.9/17.9	330	285	OUT	*N_2 Gas Injection 1.2 L/S	22	350	190	650	375	700	490	655	–	700	755	703	–	–	542	455	545	225	10	550	8	540	7	12
							646	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–
1285	50	17.9/17.9	300	262	OUT	*N_2 Gas Injection 1.2 L/S	15	20	16	500	195	530	230	430	495	490	510	510	635	635	475	465	505	180	115	550	10	540	10	2
							605	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–
1286	50	17.9/17.9	315	260	OUT	*N_2 Gas Injection 2.2 L/S	10	20	12	–	–	–	–	–	–	–	–	–	645	630	490	430	680	220	143	570	13	550	10	10
							170	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–

– No Quenching or No Complete Refilling
x Faulty Thermocouple
* Showed No Water Penetration to the Channel During the Entire Time of Testing
Note: All times indicated are estimated from the initiation of water injection to the headers.

Table A1: Feeder Quench and Refilling Times. Tests of Report CWAPD – 480
ii – Double Channel Tests – Bottom Channel Feeders

Test No.	Channel Power (kW)	Break Size Inlet/-Outlet %	Initial Feeder Temperature (°C)		First Refilled Feeder	Other Conditions	Quench Times (s) / Refilling Times (s)																								
			In T/C 26	Out T/C 32			Outlet Feeder Thermocouples												Inlet Feeder Thermocouples											
							T/C 31	T/C 32	T/C 57	T/C 58	T/C 29	T/C 30	T/C 53	T/C 51	T/C 52	T/C 49	T/C 47	T/C 4	T/C 3	T/C 45	T/C 43	T/C 41	T/C 42	T/C 39	T/C 27	T/C 28	T/C 35	T/C 36	T/C 25	T/C 26
1271	0	100/100	359	297	IN		13	25	48	65	75	130	160	230	365	370	365	360	235	235	235	180	235	208	35	206	8	95	8	65
							–	–	550	–	550	570	520	500	500	487	480	470	350	370	370	295	300	290	230	232	190	230	110	190
1272	0	6.4/6.4	345	290	IN		30	35	35	45	45	95	55	115	250	250	245	240	150	150	147	135	160	85	20	145	8	115	8	15
							–	–	325	–	325	325	380	337	340	317	315	315	225	225	195	210	205	165	155	160	135	150	115	135
1274	0	100/70	360	285	OUT		33	23	33	77	55	113	123	127	245	163	313	261	408	413	423	261	420	263	93	160	10	83	8	46
							253	253	258	273	300	303	303	343	343	343	423	423	–	–	–	–	–	–	–	–	–	–	–	–
1276	0	100/70	372	295	OUT	Orifice at Inlet Feeder	28	36	30	98	62	105	122	130	233	165	312	270	435	440	447	290	440	240	105	305	5	120	5	50
							120	290	290	290	310	310	310	295	370	432	430	430	640	642	646	–	–	–	–	–	–	–	–	–
1279	0	100/100	348	275	IN	Orifice at Inlet Feeder	35	35	38	95	85	115	135	215	475	433	428	425	305	315	315	220	310	180	22	288	7	100	7	52
							–	–	–	–	–	–	–	–	–	–	550	550	415	415	385	390	395	335	325	335	285	325	285	285
1293	0	100/20	355	270	OUT		3	23	25	30	28	60	40	43	63	52	65	60	155	160	180	160	165	183	180	195	8	198	10	195
							63	63	65	66	68	95	140	145	165	160	163	165	255	255	255	300	300	340	385	385	385	388	385	385

– No Quenching or No Complete Refilling
x Faulty Thermocouple
Note: All times indicated are estimated from the initiation of water injection to the headers.

Table A1: Feeder Quench and Refilling Times. Tests of Report CWAPD – 480
iii – Double Channel Tests – Top Channel Feeders

Test No.	Channel Power (kW)	Break Size Inlet/-Outlet %	Initial Feeder Temperature (°C)		First Refilled Feeder	Other Conditions	Quench Times (s) / Refilling Times (s)																		
							Outlet Feeder Thermocouples										Inlet Feeder Thermocouples								
			In T/C 18	Out T/C 24			T/C 23	T/C 24	T/C 55	T/C 56	T/C 21	T/C 22	T/C 67	T/C 65	T/C 66	T/C 2	T/C 1	T/C 63	T/C 64	T/C 19	T/C 20	T/C 37	T/C 38	T/C 17	T/C 18
1271	0	100/100	350	293	OUT		15	40	15	67	70	80	130	156	215	210	350	102	360	28	110	15	100	15	45
							70	90	200	205	208	210	210	312	280	315	540								
1272	0	6.4/6.4	338	295	OUT		6	6	33	40	35	85	45	100	145	125	230	225	225	20	113	8	105	8	11
							115	115	128	125	145	148	170	200	215	200	355	355							
1274	0	100/70	350	295	OUT		8	29	33	93	53	133	150	133	273	163	223	88	303	19	123	8	93	8	23
							63	73	253	293	313	313	310	443	435	453									
1276	0	100/70	360	295	OUT	Orifice at Inlet Feeder	10	30	30	70	40	120	125	108	270	180	260	190	465	100	130	9	125	9	20
							68	70	290	290	300	292	300	400	460	480								690	700
1279	0	100/100	347	285	IN	Orifice at Inlet Feeder	13	45	47	95	65	115	135	125	290	285	180	165	415	35	135	7	90	7	20
							75	90	282	280	285	288	285	355	375	395									
1293	0	100/20	340	270	OUT		2	5	25	38	30	40	36	35	60	42	165	185	195	200	200	9	215	7	23
							65	65	68	68	85	85	70	165	165	165	325	350	330	395	365	395	395	395	395

– No Quenching or No Complete Refilling
x Faulty Thermocouple
Note: All times indicated are estimated from the initiation of water injection to the headers.

Table A2: Feeder Quench and Refilling Times. Tests of Report CWAPD-481
i – Single (Bottom) Channel Tests

Test No.	Channel Power (kW)	Break Size Inlet/-Outlet %	Initial Feeder Temperature (°C)		First Refilled Feeder	Other Conditions	Quench Times (s) / Refilling Times (s)																									
							Outlet Feeder Thermocouples												Inlet Feeder Thermocouples											
			In T/C 26	Out T/C 32			T/C 31	T/C 32	T/C 57	T/C 58	T/C 29	T/C 30	T/C 53	T/C 51	T/C 52	T/C 49	T/C 47	T/C 4	T/C 3	T/C 45	T/C 43	T/C 41	T/C 42	T/C 39	T/C 27	T/C 28	T/C 35	T/C 36	T/C 25	T/C 26
1303	0	6.4/6.4	350	295	OUT		x	30	28	390	37	440	40	110	460	112	180	180	480	487	485	480	490	380	260	477	10	470	10	15
							x	460	140	460	540	555	575	640	680	650	680	680	1220	1236	–	–	–	–	–	–	950	–	910	–
1304	0	100/100	348	295	IN		x	28	75	135	435	435	435	420	415	418	415	410	247	320	175	105	325	145	40	150	20	135	10	15
							x	–	–	–	–	–	–	530	–	507	502	500	365	366	347	347	350	338	335	338	313	320	305	307
1305	50	100/100	355	300	IN		x	28	30	70	565	570	543	548	545	546	542	535	290	330	190	115	375	123	40	352	12	350	12	30
							x	–	–	–	–	–	–	–	–	410	705	700	476	476	450	445	435	445	440	433	430	430	410	410
1306	0	100/100	310	250	IN		x	15	18	40	39	83	330	313	315	316	314	310	185	235	145	110	205	107	26	195	10	80	6	25
							x	–	–	–	–	–	–	–	–	400	388	385	268	288	273	275	277	268	265	268	220	230	165	170
1307	0	100/100	260	207	IN		x	17	20	285	285	290	285	275	272	274	272	268	157	165	112	93	230	90	35	97	15	82	8	30
							x	–	–	–	–	362	360	355	360	355	330	325	255	255	255	255	257	225	220	225	210	213	195	197
1308	0	100/100	143	120	OUT		x	10	8	12	10	15	11	18	25	18	18	18	23	25	28	27	29	12	8	10	5	31	3	7
							x	10	8	12	10	15	11	18	25	18	18	18	–	–	–	108	–	84	82	83	79	83	77	80

– No Quenching or No Complete Refilling
x Faulty Thermocouple
Note: All times indicated are estimated from the initiation of water injection to the headers.

Table A2: Feeder Quench and Refilling Times. Tests of Report CWAPD-481
ii – Single (Top) Channel Tests

Test No.	Channel Power (kW)	Break Size Inlet/-Outlet %	Initial Feeder Temperature (°C)		First Refilled Feeder	Other Conditions	Quench Times (s) / Refilling Times (s)																		
							Outlet Feeder Thermocouples										Inlet Feeder Thermocouples								
			In T/C 18	Out T/C 24			T/C 23	T/C 24	T/C 55	T/C 56	T/C 21	T/C 22	T/C 67	T/C 65	T/C 66	T/C 2	T/C 1	T/C 63	T/C 64	T/C 19	T/C 20	T/C 37	T/C 38	T/C 17	T/C 18
1309	0	6.4/6.4	348	290	OUT		1 170	7 172	30 252	70 290	40 390	190 390	45 410	45 540	110 590	50 580	210 –	200 –	290 –	20 –	530 –	8 890	530 970	8 810	18 825
1310	0	100/100	338	284	IN		1 600	13 600	20 595	35 595	45 590	113 590	113 585	355 515	355 515	340 505	125 325	93 325	235 327	40 278	114 278	5 265	70 273	5 245	25 255
1311	50	100/100	340	290	IN		5 –	20 –	25 –	70 –	395 –	395 –	398 –	378 –	378 –	365 615	105 330	90 310	260 410	46 260	105 262	8 225	57 250	7 215	25 220
1312	0	100/100	285	250	IN		1 –	10 –	20 –	30 –	65 –	66 –	65 –	277 –	278 385	265 385	82 245	85 235	215 265	42 210	85 213	3 200	60 205	2 175	20 180
1313	0	100/100	205	202	IN		1 –	2 –	8 –	54 –	94 –	155 –	157 –	147 225	145 229	140 215	82 125	60 130	107 155	35 100	87 110	15 90	68 95	5 65	7 65
1314	0	100/100	130	105	OUT		5 5	15 15	8 8	50 50	13 13	18 18	12 12	17 17	20 20	18 18	120 –	88 –	– –	45 75	46 85	40 45	45 52	5 40	7 43

– No Quenching or No Complete Refilling
x Faulty Thermocouple
Note: All times indicated are estimated from the initiation of water injection to the headers.

Table A2: Feeder Quench and Refilling Times. Tests of Report CWAPD-481
iii – Double Channel Tests-Bottom Channel Feeders

Test No.	Channel Power (kW)	Break Size Inlet/-Outlet %	Initial Feeder Temperature (°C)		First Refilled Feeder	Other Conditions	Quench Times (s) / Refilling Times (s)																							
							Outlet Feeder Thermocouples												Inlet Feeder Thermocouples											
			In T/C 26	Out T/C 32			T/C 31	T/C 32	T/C 57	T/C 58	T/C 29	T/C 30	T/C 53	T/C 51	T/C 52	T/C 49	T/C 47	T/C 4	T/C 3	T/C 45	T/C 43	T/C 41	T/C 42	T/C 39	T/C 27	T/C 28	T/C 35	T/C 36	T/C 25	T/C 26
1294	0	100/100	350	280	IN		35	35	x	115	390	385	387	380	380	380	374	368	347	256	175	100	250	132	61	115	10	100	10	35
							–	–	x	–	–	–	–	–	–	474	472	470	353	253	245	295	295	245	245	240	238	240	237	237
1295	0	100/100	325	270	IN		x	32	40	75	98	340	170	330	332	337	330	325	207	228	145	43	210	116	40	110	6	75	5	42
							x	–	–	–	–	–	–	440	450	408	402	400	310	310	290	290	292	252	252	252	195	200	180	190
1296	0	100/100	280	258	IN		x	23	68	77	80	115	108	203	200	200	197	198	138	130	128	87	130	75	65	x	35	60	8	30
							x	–	–	–	–	–	–	–	–	–	260	260	190	190	165	160	210	132	130	x	125	128	112	125
1297	0	100/100	248	200	OUT		x	14	17	92	21	83	50	103	110	110	122	120	168	170	174	72	165	60	43	80	8	50	7	15
							x	90	92	93	133	130	130	141	145	153	153	153	235	236	236	–	–	–	–	–	–	–	–	–
1298	0	100/100	310	250	IN		x	15	20	72	56	105	128	152	200	165	336	332	200	235	195	95	213	95	45	130	9	55	7	28
							x	–	–	–	–	–	–	–	–	432	413	412	310	310	303	300	305	255	256	256	213	220	60	70
1299	0	100/100	347	300	IN		x	27	40	110	320	325	323	210	305	307	305	297	150	173	168	61	167	133	47	133	8	75	8	40
							x	–	–	–	–	–	–	–	–	415	397	395	295	295	230	230	233	165	163	165	120	157	55	75
1301	50	100/100	350	310	IN		x	20	22	58	58	256	253	405	410	407	405	400	256	256	183	115	260	123	60	100	10	80	10	25
							x	–	–	–	–	–	–	–	–	555	553	550	380	380	285	280	300	280	270	257	230	255	70	100
1302	0	6.4/6.4	350	300	IN		x	30	25	35	35	120	53	153	280	285	280	275	178	190	175	164	210	110	17	160	13	135	7	14
							x	360	400	360	400	320	420	400	320	347	345	340	255	255	245	245	270	190	175	193	150	180	80	140

– No Quenching or No Complete Refilling
x Faulty Thermocouple
Note: All times indicated are estimated from the initiation of water injection to the headers.

Table A2: Feeder Quench and Refilling Times. Tests of Report CWAPD-480
iv – Double Channel Tests – Top Channel Feeders

Test No.	Channel Power (kW)	Break Size Inlet/-Outlet %	Initial Feeder Temperature (°C)		First Refilled Feeder	Other Conditions	Quench Times (s) / Refilling Times (s)																			
							Outlet Feeder Thermocouples										Inlet Feeder Thermocouples									
			In T/C 18	Out T/C 24			T/C 23	T/C 24	T/C 55	T/C 56	T/C 21	T/C 22	T/C 67	T/C 65	T/C 66	T/C 2	T/C 1	T/C 63	T/C 64	T/C 19	T/C 20	T/C 37	T/C 38	T/C 17	T/C 18
1294	0	100/100	345	287	IN		5 533	17 535	35 535	97 538	395 –	395 –	414 –	370 –	375 –	355 535	112 370	80 355	240 355	40 235	115 233	11 225	80 230	10 70	25 95
1295	0	100/100	308	262	IN		2 390	2 –	22 –	80 –	100 –	275 –	147 –	255 –	255 –	245 400	85 290	63 280	190 270	48 185	90 185	10 160	70 165	8 50	10 70
1296	0	100/100	273	262	IN		2 305	10 306	15 350	75 353	75 –	130 –	130 –	190 –	195 –	180 305	98 200	70 200	131 210	52 140	70 143	17 105	55 107	5 40	8 50
1297	0	100/100	230	209	IN		5 –	7 –	15 –	45 –	25 –	150 –	70 –	143 220	150 –	137 220	67 138	60 113	90 125	33 90	60 95	8 85	40 88	5 28	10 40
1298	0	100/100	295	247	IN		3 –	5 –	20 –	70 –	60 –	80 –	80 –	250 –	250 –	240 –	70 280	65 250	150 252	40 150	80 147	6 145	50 145	3 45	2 50
1299	0	100/100	346	275	IN		5 467	20 –	28 472	110 –	329 –	328 –	345 –	310 –	317 –	290 465	98 300	77 300	170 303	33 157	105 168	10 110	58 150	10 30	35 55
1301	50	100/100	345	295	IN		2 –	10 –	22 –	70 –	73 –	257 –	440 –	417 –	410 –	405 670	90 375	90 370	242 380	45 245	90 142	5 220	56 140	3 40	15 65
1302	0	6.4/6.4	[illegible]	270	OUT		1 30	3 30	25 135	35 155	40 160	42 165	50 163	80 200	98 250	93 205	242 330	250 335	252 330	50 365	170 340	6 365	125 340	3 335	10 340

– No Quenching or No Complete Refilling
x Faulty Thermocouple
Note: All times indicated are estimated from the initiation of water injection to the headers.

Table A3: Feeder Quench and Refilling Times. Tests of Report SL-010
i – Single (Bottom) Channel Tests

Test No.	Channel Power (kW)	Break Size Inlet/-Outlet %	Initial Feeder Temperature (°C)		First Refilled Feeder	Other Conditions	Quench Times (s) / Refilling Times (s)																								
							Outlet Feeder Thermocouples												Inlet Feeder Thermocouples											
			In T/C 26	Out T/C 32			T/C 31	T/C 32	T/C 57	T/C 58	T/C 29	T/C 30	T/C 53	T/C 51	T/C 52	T/C 49	T/C 47	T/C 4	T/C 3	T/C 45	T/C 43	T/C 41	T/C 42	T/C 39	T/C 27	T/C 28	T/C 35	T/C 36	T/C 25	T/C 26
1401	0	100/100	240	202	IN		6 273	15 285	16 272	80 285	80 270	95 255	95 270	170 228	171 230	168 212	166 210	165 210	141 151	140 151	112 150	85 150	129 170	45 130	40 130	125 148	10 118	85 130	8 100	20 110
1402	0	100/100	273	250	IN		5 493	20 455	13 492	348 455	335. 465	350 450	335 455	32 413	322 413	330 386	321 385	317 385	235 302	270 300	235 290	105 292	237 295	73 237	35 235	230 245	25 225	157 230	5 205	25 210
1403	0	100/100	327	300	IN		10 –	30 –	530 –	540 –	515 –	525 –	520 645	500 613	502 620	500 598	495 595	490 595	313 495	475 495	248 473	140 473	397 475	140 397	42 395	313 403	35 385	165 385	5 335	30 340
1404	0	100/100	252	215	IN		15 395	15 –	331 –	333 –	330 –	332 –	330 440	321 395	320 400	317 387	315 385	310 385	235 303	280 303	155 300	110 300	248 300	85 295	30 245	235 255	10 233	195 230	5 220	27 227
1405	50	100/100	235	218	IN		13 444	15 455	17 442	260 455	255 440	260 427	258 430	246 390	247 385	243 383	241 380	240 380	160 190	170 189	127 185	90 180	170 265	50 165	11 160	150 170	10 150	122 163	7 140	17 143
1406	50	100/100	285	255	IN		6 –	15 –	15 –	398 –	390 –	398 –	390 580	375 540	375 540	374 527	372 525	370 525	262 318	295 318	162 305	100 305	365 395	80 262	25 260	260 305	16 246	220 360	3 240	5 240
1407	50	100/100	325	300	IN		10 –	20 –	640 –	637 –	620 –	635 –	630 –	600 790	610 790	600 780	595 780	590 780	440 527	473 525	220 520	130 530	472 640	110 472	17 472	470 520	15 444	240 472	5 442	25 470
1408	0	100/100	325	290	IN		15 675	20 662	242 675	520 662	505 665	510 660	515 655	500 610	495 610	500 592	495 590	490 590	365 465	436 465	245 455	142 455	395 495	95 454	14 395	330 410	13 385	285 387	3 350	27 385
1409	0	6.4/6.4	242	218	OUT		8 55	10 80	28 70	30 155	31 210	148 210	35 230	40 285	82 310	45 290	80 315	80 317	168 520	330 620	335 650	190 –	330 –	168 –	160 –	305 –	10 –	170 –	10 515	10 –
1410	0	6.4/6.4	285	280	OUT		2 200	22 210	20 210	82 310	20 318	270 440	90 340	158 445	260 480	165 450	180 470	180 473	480 –	488 –	495 –	488 –	490 –	326 –	275 –	518 –	10 –	520 –	5 640	15 –
1411	0	6.4/6.4	320	290	OUT		6 390	10 490	30 490	82 570	75 580	390 580	100 590	165 640	380 370	200 640	210 680	203 683	700 –	708 –	525 –	525 –	710 –	380 –	380 –	670 –	350 –	520 –	8 870	10 –

– No Quenching or No Complete Refilling
x Faulty Thermocouple
Note: All times indicated are estimated from the initiation of water injection to the headers.

Table A3: Feeder Quench and Refilling Times. Tests of Report SL-010
ii – Double Channel Tests–Bottom Channel Feeders

Test No.	Channel Power (kW)	Break Size Inlet/-Outlet %	Initial Feeder Temperature (°C)		First Refilled Feeder	Other Conditions	Quench Times (s) / Refilling Times (s)																									
							Outlet Feeder Thermocouples												Inlet Feeder Thermocouples												
			In T/C 26	Out T/C 32			T/C 31	T/C 32	T/C 57	T/C 58	T/C 29	T/C 30	T/C 53	T/C 51	T/C 52	T/C 49	T/C 47	T/C 4	T/C 3	T/C 45	T/C 43	T/C 41	T/C 42	T/C 39	T/C 27	T/C 28	T/C 35	T/C 36	T/C 25	T/C 26
1412	0	6.4/6.4	273	220	OUT		5 90	18 90	20 180	32 180	20 198	35 198	35 200	60 222	160 230	68 225	110 230	70 232	240 305	245 305	246 307	242 322	245 350	246 355	45 360	255 400	25 362	165 400	12 362	25 400
1413	0	6.4/6.4	295	253	OUT		2 170	28 282	18 230	38 310	20 342	40 342	18 345	56 368	155 370	72 365	160 375	162 376	390 –	394 –	396 –	390 –	392 –	402 –	290 –	402 –	9 –	287 –	5 –	15 –
1414	0	6.4/6.4	330	290	IN		35 592	42 592	45 590	250 592	46 590	335 592	68 588	430 510	435 528	437 505	433 505	430 505	335 413	355 410	315 400	300 400	348 410	290 355	280 345	295 350	7 325	285 315	6 280	25 410
1415	0	6.4/6.4	248	220	OUT		10 90	12 95	15 115	30 150	27 170	32 172	32 172	55 191	55 195	53 198	64 200	60 201	205 252	209 252	210 252	205 275	205 285	48 330	20 320	220 355	9 322	228 355	5 322	15 355
1416	0	100/100	230	210	IN		7 340	12 355	15 340	97 355	76 340	117 355	117 330	195 277	197 272	202 255	191 255	190 255	137 192	137 190	136 167	67 157	143 177	57 143	23 142	107 152	14 127	44 127	6 127	14 127
1417	0	100/100	290	250	IN		9 440	22 440	26 440	80 440	80 438	257 410	250 425	240 330	240 340	241 317	239 317	237 317	117 238	157 236	139 232	54 188	157 227	92 158	52 157	105 166	27 150	82 152	5 150	22 152
1418	0	100/100	320	295	IN		16 563	22 580	60 563	102 580	374 560	378 580	388 558	359 466	360 470	359 445	357 445	354 445	212 345	271 340	186 290	67 287	228 336	118 258	30 262	168 295	6 252	87 250	3 202	27 220
1419	50	100/100	280	255	IN		10 –	10 –	12 –	115 –	310 –	158 –	320 –	300 450	305 460	305 440	303 440	300 440	190 280	210 275	190 270	115 212	195 250	40 190	35 190	170 195	12 175	85 178	10 175	10 175
1420	50	100/100	325	293	IN		10 715	30 742	14 715	105 742	95 715	272 740	450 715	438 590	434 600	442 580	438 580	430 580	240 400	340 380	200 350	120 350	296 353	120 300	60 300	165 300	10 300	105 290	8 266	34 260
1421	0	100/100	320	300	IN		6 –	26 –	52 –	167 –	344 –	352 –	352 –	337 456	337 458	341 437	336 437	327 437	177 310	240 309	212 307	75 257	182 297	88 212	47 207	162 210	12 202	122 202	3 202	17 202
1422	50	100/100	260	213	IN		15 500	18 540	18 500	118 540	30 500	140 510	72 505	145 380	230 380	232 360	231 360	230 360	110 197	130 195	100 190	82 152	132 200	40 130	45 130	35 150	20 130	70 130	2 130	3 130

– No Quenching or No Complete Refilling
x Faulty Thermocouple
Note: All times indicated are estimated from the initiation of water injection to the headers.

Table A3: Feeder Quench and Refilling Times. Tests of Report SL-010
iii – Double Channel Tests – Top Channel Feeders

Test No.	Channel Power (kW)	Break Size Inlet/-Outlet %	Initial Feeder Temperature (°C)		First Refilled Feeder	Other Conditions	Quench Times (s) / Refilling Times (s)																			
							Outlet Feeder Thermocouples										Inlet Feeder Thermocouples									
			In T/C 18	Out T/C 24			T/C 23	T/C 24	T/C 55	T/C 56	T/C 21	T/C 22	T/C 67	T/C 65	T/C 66	T/C 2	T/C 1	T/C 63	T/C 64	T/C 19	T/C 20	T/C 37	T/C 38	T/C 17	T/C 18
1412	0	6.4/6.4	260	218	IN		2 –	3 –	26 –	36 –	30 –	110 –	43 –	97 –	110 –	90 300	195 240	198 240	220 245	45 207	165 215	18 190	160 190	10 145	12 145
1413	0	6.4/6.4	290	250	IN		1 435	1 460	26 435	35 460	28 435	33 460	40 435	65 430	138 460	95 400	322 380	320 380	342 395	285 345	390 350	9 325	285 325	5 192	10 200
1414	0	6.4/6.4	320	280	OUT		1 100	17 255	35 262	40 265	48 305	40 308	68 309	92 355	250 360	160 360	375 475	385 480	390 490	400 500	395 530	14 500	296 530	12 500	15 530
1415	0	6.4/6.4	240	215	IN		1 290	3 320	25 290	30 320	30 290	32 320	36 290	62 272	150 320	80 220	170 205	156 202	180 200	18 284	155 180	16 150	45 160	5 90	7 150
1416	0	100/100	225	215	IN		7 –	8 –	17 –	68 –	190 –	190 –	200 –	177 –	177 320	172 272	60 190	35 172	117 177	26 117	37 120	6 112	61 112	4 87	6 87
1417	0	100/100	282	250	IN		2 367	7 –	17 450	107 –	82 467	107 –	270 467	255 368	252 386	236 374	92 257	46 240	143 250	45 143	97 165	7 140	60 142	5 132	7 136
1418	0	100/100	312	280	IN		2 500	7 –	22 –	107 –	367 –	360 –	387 –	343 507	340 521	323 502	97 360	63 350	329 365	47 212	130 227	5 212	59 232	3 212	9 232
1419	50	100/100	268	250	IN		10 –	10 –	22 –	135 –	307 –	300 –	320 –	285 –	288 –	268 525	62 275	55 270	160 265	35 160	65 175	12 155	55 160	10 90	16 90
1420	50	100/100	320	280	IN		7 666	10 –	27 –	100 –	430 790	430 –	458 790	410 683	410 –	395 670	82 410	62 390	260 390	60 265	105 265	7 260	100 260	3 223	15 226
1421	0	100/100	310	280	IN		5 –	11 –	7 –	176 –	342 –	338 –	377 –	320 –	330 –	310 497	97 357	87 336	181 365	47 167	107 180	7 167	70 170	2 167	16 167
1422	50	100/100	240	215	IN		2 450	2 –	18 –	62 –	110 –	140 –	250 –	230 490	230 480	220 460	88 220	70 230	120 235	35 115	80 130	15 110	60 110	5 110	10 110

– No Quenching or No Complete Refilling
x Faulty Thermocouple
Note: All times indicated are estimated from the initiation of water injection to the headers.

Table A4: Feeder Quench and Refilling Times. Tests of Report WNRE-613
i – Single (Bottom) Channel Tests

Test No.	Channel Power (kW)	Break Size Inlet/-Outlet %	Initial Feeder Temperature (°C)		First Refilled Feeder	Other Conditions	Quench Times (s) / Refilling Times (s)																						
			In T/C 26	Out T/C 32			Outlet Feeder Thermocouples											Inlet Feeder Thermocouples											
							T/C 31	T/C 32	T/C 57	T/C 29	T/C 30	T/C 53	T/C 51	T/C 52	T/C 49	T/C 47	T/C 4	T/C 3	T/C 45	T/C 43	T/C 41	T/C 42	T/C 39	T/C 27	T/C 28	T/C 35	T/C 36	T/C 25	T/C 26
1081	0	100/100	282	250	OUT		20	20	23	65	265	102	298	350	315	377	352	457	458	460	463	464	477	130	300	30	275	10	20
							322	325	330	340	342	350	385	385	400	410	410	560	560	560	560	560	–	–	–	–	–	–	–
1082	00	100/100	320	293	OUT		5	15	70	38	420	318	395	515	460	670	470	770	772	774	777	780	370	180	410	134	355	8	18
							660	660	660	660	660	670	675	675	680	700	705	880	880	880	900	900	–	–	–	–	–	–	–

– No Quenching or No Complete Refilling
x Faulty Thermocouple
Note: All times indicated are estimated from the initiation of water injection to the headers.

Table A4: Feeder Quench and Refilling Times. Tests of Report WNRE-613
ii – Double Channel Tests – Bottom Channel Feeders

Test No.	Channel Power (kW)	Break Size Inlet/-Outlet %	Initial Feeder Temperature (°C)		First Refilled Feeder	Other Conditions	Quench Times (s) / Refilling Times (s)																						
							Outlet Feeder Thermocouples											Inlet Feeder Thermocouples											
			In T/C 26	Out T/C 32			T/C 31	T/C 32	T/C 57	T/C 29	T/C 30	T/C 53	T/C 51	T/C 52	T/C 49	T/C 47	T/C 4	T/C 3	T/C 45	T/C 43	T/C 41	T/C 42	T/C 39	T/C 27	T/C 28	T/C 35	T/C 36	T/C 25	T/C 26
1108	0	6.4/6.4	350	300	IN		15	18	40	42	65	70	385	385	348	345	318	200	205	188	178	206	117	20	165	10	75	9	15
							–	–	375	375	375	460	455	455	425	425	425	325	325	310	305	320	245	220	223	185	190	155	155
1115	0	100/100	342	300	OUT		35	35	40	105	175	170	175	315	265	355	315	460	462	483	470	471	164	15	175	13	145	5	20
							285	285	290	315	315	315	385	385	385	415	417	575	575	575	625	625	630	630	630	630	720	720	720
1121	50	100/100	340	300	IN		70	72	80	110	360	190	700	702	692	692	685	520	530	445	285	460	220	42	240	40	235	18	40
							–	–	–	–	–	–	–	–	884	882	880	572	572	572	570	570	520	517	517	515	517	510	510

Table A4: Feeder Quench and Refilling Times. Tests of Report WNRE-613
iii – Double Channel Tests – Top Channel Feeders

Test No.	Channel Power (kW)	Break Size Inlet/-Outlet %	Initial Feeder Temperature (°C)		First Refilled Feeder	Other Conditions	Quench Times (s) / Refilling Times (s)																		
							Outlet Feeder Thermocouples										Inlet Feeder Thermocouples								
			In T/C 18	Out T/C 24			T/C 23	T/C 24	T/C 55	T/C 56	T/C 21	T/C 22	T/C 67	T/C 65	T/C 66	T/C 2	T/C 1	T/C 63	T/C 64	T/C 19	T/C 20	T/C 37	T/C 38	T/C 17	T/C 18
1108	0	6.4/6.4	350	300	OUT		15	15	13	36	38	50	65	90	165	155	300	302	302	20	80	5	68	2	4
							30	35	140	175	195	198	198	265	320	267	405	405	405	320	320	320	320	–	–
1115	0	100/100	340	300	IN		35	43	45	160	125	180	215	471	473	460	27	25	325	20	182	10	140	5	20
							–	–	–	–	–	–	780	680	680	680	435	435	435	315	315	295	297	150	150
1121	50	100/100	340	300	IN		20	80	70	160	90	210	230	630	635	600	260	220	382	48	210	35	160	18	40
							–	–	–	–	–	–	–	–	–	–	560	560	560	395	396	390	392	350	350

– No Quenching or No Complete Refilling
x Faulty Thermocouple
Note: All times indicated are estimated from the initiation of water injection to the headers.

Table A5: Feeder Quench and Refilling Times. Tests of Report CWAP-460
Single Channel (Bottom) Tests, Break Size 17.9% and Channel Power = 50 kW

Test No.	Gas Injection (L/S STP)	Break Location	Initial Feeder Temperature (°C)		First Refilled Feeder	Quench Times (s) / Refilling Times (s)										Remarks
						Outlet Feeder Thermocouples					Inlet Feeder Thermocouples					
			In T/C 26	Out T/C 32		T/C 32	T/C 57	T/C 30	T/C 52	T/C 4	T/C 3	T/C 42	T/C 28	T/C 36	T/C 25	
1258	–	IN and OUT	290	260	OUT	8 70	15 160	125 192	125 250	125 275	300 575	310 590	335 –	345 –	8 600	
1259	2 (N_2)	IN and OUT	300	248	–	20 –	22 –	– –	– –	– –	– –	– –	– –	– –	20 –	No water penetration to the channel
1260	1.05 (N_2)	IN and OUT	290	255	OUT	6 180	7 185	130 232	160 327	143 342	390 –	400 –	x x	420 –	18 –	
1261	–	OUT	288	245	IN	77 148	x x	82 138	69 120	67 120	37 55	41 60	32 53	18 40	6 23	
1262	4 (N_2)	OUT	290	245	IN	78 160	81 155	81 155	69 147	69 125	31 69	45 67	25 53	22 43	5 22	
1263	4.3 (N_2)	OUT	290	245	IN	80 150	83 145	83 145	71 125	70 125	36 71	36 67	23 53	10 45	3 20	
1264	2 (He)	IN and OUT	295	260	–	10 –	30 –	– –	– –	– –	– –	– –	– –	42 –	10 –	No water penetration to the channel
1265	1.05 (N_2)	IN and OUT	280	245	OUT	12 100	16 120	120 180	123 280	135 292	330 –	337 –	360 –	380 –	10 –	

– No Quenching or No Complete Refilling
x Faulty Thermocouple
Note: All times indicated are estimated from the initiation of water injection to the headers.

APPENDIX B

AN OVERVIEW OF THE RD-14 REFILLING EXPERIMENTS

The RD-14 test facility is a full-elevation model representing the CANDU primary heat transport system. The facility is located at Whiteshell Nuclear Research Establishment (WNRE). The facility was used to perform a series of experiments simulating the blowdown and refilling phases of a loss-of-coolant accident (LOCA). Although, detailed analysis of the RD-14 data is not considered part of the present work, this Appendix is aimed at providing an overview of these experiments. Analysis of few experiments was presented earlier in Ref. [24].

A schematic of the loop is shown in figure B1. Both the primary and secondary systems in CANDU reactors are simulated in the loop. The primary system has two 6 m long, 5.5 MW parallel channels representing two passes through the reactor core. Each channel contains 37 electrically heat fuel element simulators. Heat removal from the primary system is achieved by two full-height steam generators. The channel and steam generators are connected through four headers and feeders to complete a full elevation of a typical CANDU figure-of-eight primary loop. Other loop components are shown in figure B1.

All RD-14 experiments were started with stable single phase flow through the primary system. The transient was initiated by opening a fast acting valve connected to inlet header #4, as shown in figure B1, to simulate the break. Water was then injected into the loop when its pressure fell below the injection pressure. Two injection pressures were used, 13 and 5.5 MPa. Two types of experiments were carried out, small and large break tests.

The small break tests simulated a feeder-sized break at the inlet header. During these tests the loop remained in a stable condition and all flows remained in the normal directions until the end of the transient.

The large break tests represented a guillotine break of the inlet header. During these, very complicated thermal-hydraulics behaviour was encountered. Under certain conditions, flow reversal was encountered downstream of the break and almost complete flow stagnation occured upstream of the break. Accordingly, one channel remained cooled while the temperature in the other increased. Throughout the transient and until the termination of the tests, the injected water failed to reach the hot channel.

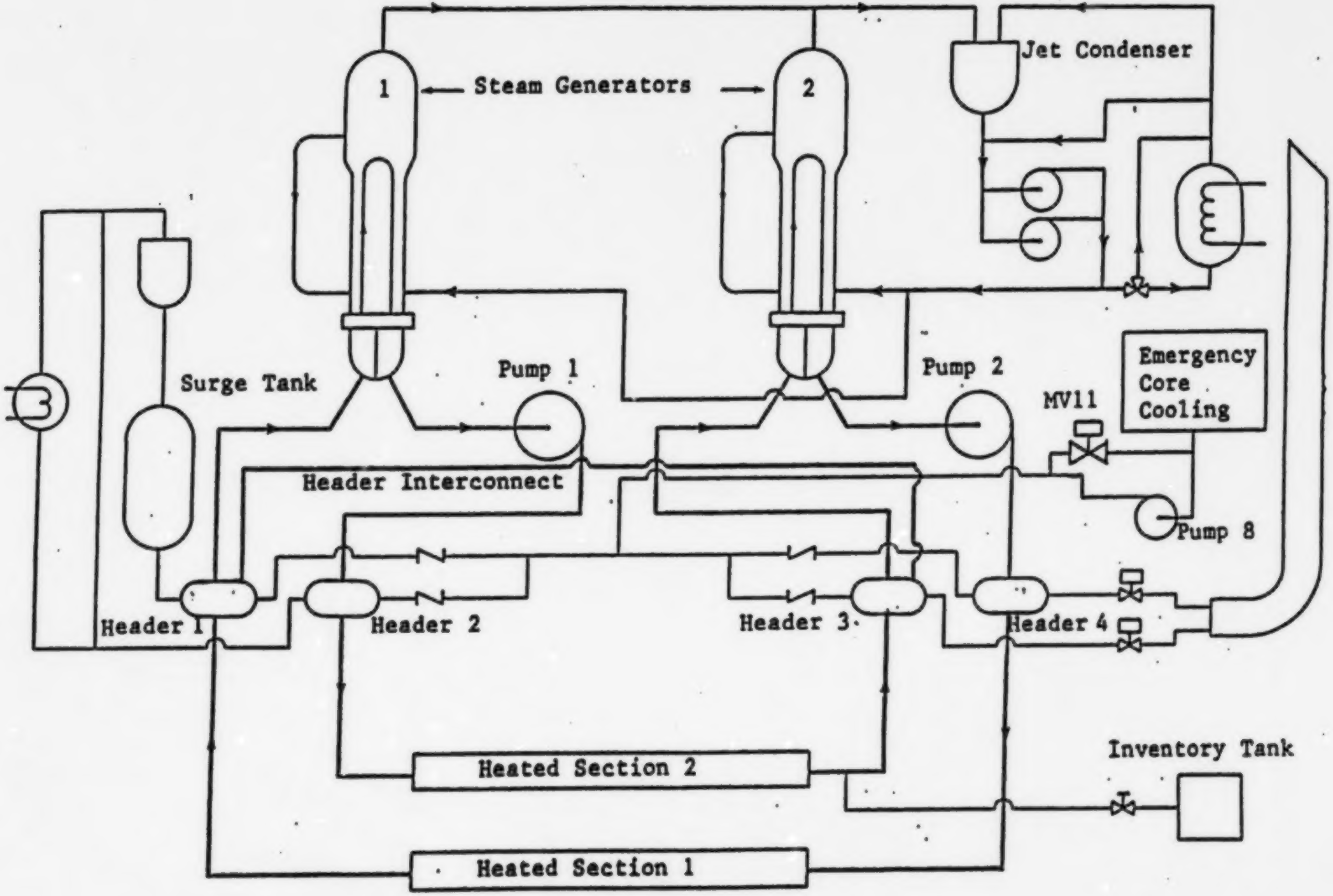

Steam Generators
1
2
Jet Condenser
Surge Tank
Pump 1
Pump 2
MV11
Emergency Core Cooling
Pump 8
Header Interconnect
Header 1
Header 2
Header 3
Header 4
Inventory Tank
Heated Section 2
Heated Section 1

FIGURE B1 : SCHEMATIC DIAGRAM OF RD-14 LOOP